

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

A Golden Ticket to Future Occupational and Environmental Health Monitoring

by

Benjamin C. Weaver, Maj, USAF, BSC

A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

Advisor: Dr. Dennis Duffin

Maxwell Air Force Base, Alabama

October 2015

Disclaimer

The views expressed in this academic research paper are those of the author and do not reflect the official policy or position of the US government or the Department of Defense. In accordance with Air Force Instruction 51-303, it is not copyrighted, but is the property of the United States government.

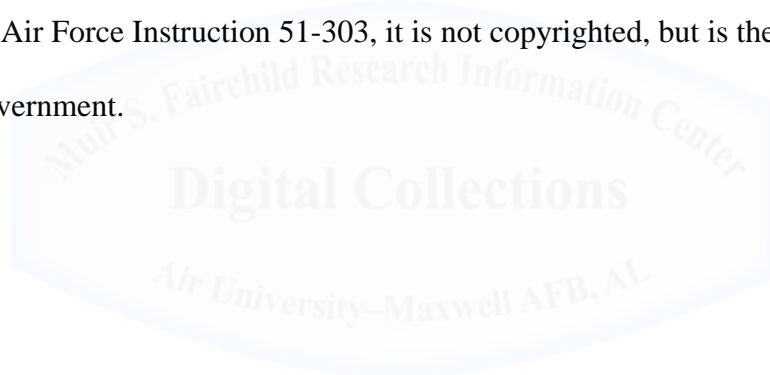


TABLE OF CONTENTS

	<i>Page</i>
DISCLAIMER	<i>ii</i>
TABLE OF CONTENTS.....	<i>iii</i>
LIST OF FIGURES	<i>v</i>
ACKNOWLEDGMENTS	<i>vi</i>
ABSTRACT.....	<i>vii</i>
Introduction.....	1
Research Question	1
Overview	1
Research Methodology and Framework	2
Research Criteria.....	3
Background	4
Monitoring and Compliance Requirements	4
BE Occupational and Environmental Monitoring Capabilities	7
Field Monitoring Capabilities	8
Laboratory Analysis Capabilities.....	9
Prevalence of Occupational Exposures in the Air Force	10
An Explanation of Focus on Chemical Hazards	12
Literature Review.....	14
Gold Nanoparticle Properties.....	14
Optical (Colorimetric) Detection of Water Contaminants.....	14
Electrochemical Detection of Water Contaminants.....	17
Detection of Volatile Organic Compounds (VOCs).....	18
Detection of Gasses.....	20
Detection of Airborne Metals	21
Detection of Biological Pathogens.....	22
Detection of Physical Hazards	24
Detection of Radiological Hazards	24
Existing Nanotechnology Detection Platforms.....	25
Conclusions.....	27
Conclusion #1 – Nanodetection Technology Does Not Meet All Evaluation Criteria....	27
Conclusion #2 – Two Broad Nanotechnology Classes – Optical and Electrochemical ..	28

Conclusion #3 – Benefits and Limitations of Each Class.....	28
Recommendations.....	29
Recommendation #1 – Enhance UV-Vis Spectroscopy with Nanotechnology.....	29
Recommendation #2 – Further Develop Microelectrode Detection Technology.....	30
Recommendation #3 – Validate the Performance of MIP Technology.....	31
Recommendation #4 – A Hybrid Platform for Airborne Metals.....	31
Overall Recommendation.....	32
Conclusion.....	33
APPENDIX A. Bioenvironmental Engineering Detection Capabilities.....	39
APPENDIX B. The 50 Most Prevalent Hazards across Air Force Installations.....	42
APPENDIX C. Results of Research Reviewed Compared to Evaluation Criteria.....	44
BIBLIOGRAPHY.....	48



LIST OF FIGURES

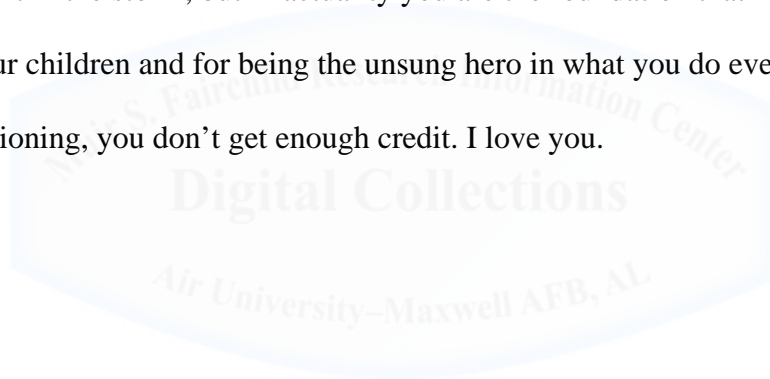
	<i>Page</i>
Figure 1. Hazard Prevalence by Class across Air Force Installations	11



ACKNOWLEDGMENTS

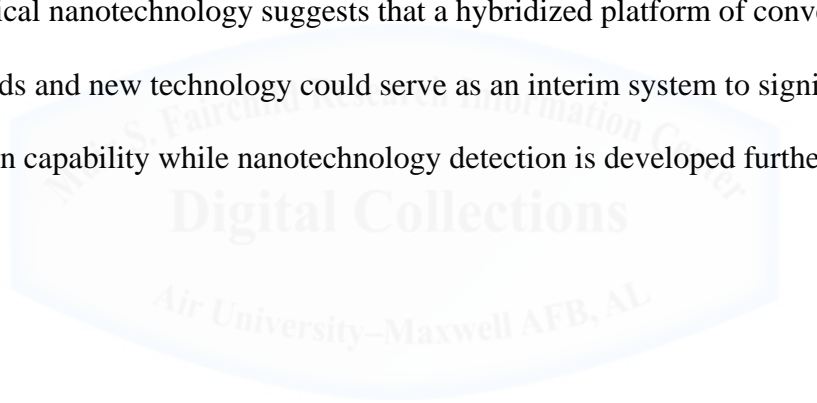
I would like to express my gratitude to the entire Air University staff for their patience and understanding throughout my journey through the program and especially the instructors who have assisted me in the research phase of it. Your flexibility and understanding allotted is the only reason I have been able to stick it out and complete this program, thank you.

To my wife, thank you for all that you are. Thank you for being able to see the forest from the trees and knowing that the countless late nights buried in my lap top completing this paper was only temporary and that you would have your husband back soon. You often tell me that I am your port in the storm, but in actuality you are the foundation that keeps me grounded. Thank you for our children and for being the unsung hero in what you do every day to keep our family unit functioning, you don't get enough credit. I love you.



ABSTRACT

This research paper evaluates the possibility of nanoparticle detection technology as a superior replacement to, or augmentation of, conventional occupational and environmental health exposure monitoring for the US Air Force Bioenvironmental Engineering career field as a reusable platform for simultaneous detection of multiple hazards and hazard classes based on sensitivity, selectivity, and real-time monitoring capability in atmospheric and aqueous environments that would be acceptable by regulatory agencies. Although research evaluated did not meet all criteria established, results reported in two broad categories of optical (colorimetric) and electrochemical nanotechnology suggests that a hybridized platform of conventional collection methods and new technology could serve as an interim system to significantly improve detection capability while nanotechnology detection is developed further to meet all required criteria.



Introduction

Research Question

Is nanoparticle detection technology a superior replacement to conventional exposure monitoring methods? The Bioenvironmental Engineering (BE) career field is responsible for the determination of exposure levels and corresponding health risk, mitigation, and compliance in the fields of industrial hygiene, environmental, drinking water, and emergency response. The current detection technology used, compounded by regulatory precision and accuracy requirements makes adequate detection and health risk assessment extremely burdensome.^{1,2,3} The resurgence of nanoparticle research and applications in the detection field has piqued the interest of many, including BE career field leaders, in search of a platform that can simultaneously detect multiple hazards with the combined benefits of lab and field analysis.⁴ Gold nanoparticle (AuNP) detection platforms, among others, show significant potential as a replacement to conventional methods based upon numerous research reports detailing their versatility, precision, and accuracy. Although this technology is still in its infancy and has some developmental milestones to reach, it is rapidly developing and is already being used in commercial systems.^{5,6,7}

Overview

In the background of this report, BE monitoring and compliance requirements will be addressed and compared to the occupational and environmental monitoring capabilities. The real-time and field monitoring segments of this capability will be detailed further before delving into a detailed discussion of the prevalence of hazards within the Air Force. Hazards will be broken down by class, sub-class, and individual chemicals.

The research methodology and framework will be explained prior to a literature review with detailed research findings of specific detection capabilities and technological variants that feature predominantly gold nanoparticle technology, with a few other variants, that are being evaluated. The literature review is segregated by the type of hazard detected (i.e. vapors, gases, organics, etc.) and physical medium that it is capable of detecting in, either air, water, or both. Some areas may contain overlap dependent upon the capability of the specific nanoparticle detection results being reviewed. Overall, the literature review will explore existing detection platforms containing nanoparticle detection technology and their performance. Evaluation results and conclusions will be made prior to an analysis and recommendations to the career field on the use of nanotechnology as a future detection platform. Lastly, a summary concluding the report will be provided.

Research Methodology and Framework

Due to the nature of the experimental research sources used in this report and the status of nanotechnology as an emerging and rapidly developing field of science, an evaluation framework and research methodology were chosen. The criteria used in the evaluation were developed to aid in answering the research question. The main focus was to determine the extent that nanotechnology detection platforms can detect hazards within the parameters of the established criteria, assess their performance, and note any deficiencies observed. Research sources used consisted primarily of experimental research literature available on nanotechnology capabilities; nanotechnology news articles and regulatory and instructional literature governing Federal, DoD, and Air Force occupational and environmental health exposure monitoring requirements were also used.

Research Criteria

In order to evaluate nanotechnology detection capabilities compared to current technology employed by the BE career field, an assessment of the regulatory monitoring requirements and current detection capabilities was critical. The next step in the evaluation process was to determine the hazards present in the Air Force that BEs are required to monitor and whether or not nanotechnology possessed the capability to detect them. This included an in-depth analysis of the occupational and environmental hazards present at installations, in emergency response scenarios, and deployed settings that must be monitored. Once these parameters were established, the feasibility of implementing this technology was explored. An ideal piece of monitoring equipment provides measurement results acceptable by regulatory agencies as a compliance sample. This means that the sample result must be within a set standard deviation and could be replicated to produce results with very little variance in the precision of measurement. Most measurement methods used by BEs only allow for the measurement of one hazard at a time; simultaneous measurement of multiple hazards would greatly enhance measurement capability. Key parameters assessed throughout the research to determine if it was suitable as a total replacement for current detection methods were: compliance with regulatory monitoring requirements, sensitivity of detection, selectivity of detection, ability to detect hazards simultaneously, ability to detect in real-time, and portability.

Cost was not used as factor in the research criteria due to the inability to predict the cost of production for these detection systems. Until a standardization of mass scale production takes place and is assessed, it will remain an unknown factor in assessing how this would impact the overall benefit of the technology. Nanoparticle synthesis is being progressively

refined as research builds upon past successes and strives to overcome failures; once standardized detection methods are established, production cost estimates can be determined.

Background

The use of nanoparticles has emerged from the imagination of science fiction authors into a very tangible technology. This technology shows great promise to enhance the exposure monitoring capabilities and achieve the challenging occupational and environmental health monitoring mission of the Bioenvironmental Engineering (BE) by overcoming the numerous monitoring protocols and analytical methods required. One of the biggest issues BE's face in achieving monitoring requirements is the sheer diversity of hazards that must be analyzed and assessed for health risks and their corresponding detection methods. Exposure monitoring is the foundation of the health risk assessment process and is critical to keeping the base population safe from occupational and environmental exposures. The predominant requirements for monitoring by BE includes the monitoring of airborne contaminants in industrial settings and water contaminants within drinking water supply systems.

Monitoring and Compliance Requirements

The United States Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) are the federal regulatory agencies responsible for enforcing workplace and environmental compliance by establishing and enforcing criteria to ensure exposures are at safe levels in the workplace and environment. The EPA was founded in 1970 with an overarching mission of preventing "significant risks to human health and the environment where they live, learn, and work" by establishing and enforcing environmental policy based on the "best available scientific information."^{8,9} The EPA establishes monitoring

requirements to assess health risk from exposure to environmental pollutants in the air, water, and soil; it also regulates the management and disposal of hazardous materials and environmental restoration policy.¹⁰ There are approximately 26 separate executive orders and acts enforced by the EPA that individuals and corporations, including the Air Force, must adhere to and comply with.¹¹

The Occupational Safety and Health Act of 1970 established the Occupational Safety and Health Administration (OSHA) as a new division of the U.S. Department of Labor.¹² This act also established the National Institute of Occupational Safety and Health (NIOSH) as a research institution “to establish standards for workplace safety and health.”¹³ OSHA standards are divided into four broad areas: construction, general industry, maritime, and agriculture. They apply to a broad range of workplace hazards including chemical safety, monitoring requirements, thermal stress, asbestos, and equipment and safety requirements.¹⁴ OSHA’s current chemical database lists 801 specific chemicals and chemical classes; 517 of these chemicals and classes listed have an associated Permissible Exposure Limit (PEL) that require monitoring if present in the workplace.¹⁵

To comply with the standards established by the EPA and OSHA, the Department of Defense (DOD) mandates environmental and occupational health compliance for all service components.^{16,17,18} The United States Air Force’s (USAF) Bioenvironmental Engineering (BE) career field serves as one of the Air Force components to satisfy the DOD requirement in tandem with other medical, civil engineering, and safety career fields.¹⁹ BEs provide exposure data collected through various field screening and laboratory analytical methods to determine occupational and environmental exposures and associated health risks.²⁰ The Occupational and Environmental Exposure Limits (OEELs) consist of exposure limits adopted from numerous

established and recognized standards that ensure a safe and healthy workplace and environment.²¹ OEELs include exposure limits and guidelines established by federal agencies including OSHA, NIOSH, and the EPA. They also include recommended guidelines from the American Conference of Government Industrial Hygienists (ACGIH) and other regulations originating from within the DOD and USAF.²²

Once exposure data is collected, BEs conduct a health risk assessment (HRA) of the exposure by considering multiple factors including: threat source, route of exposure (inhalation, ingestion, contact, etc.), work patterns, concentration, exposure duration, and exposure frequency.²³ Following this collection process, BEs provide recommendations to control and reduce the health threat to level as low as feasible. In order of precedence, the control hierarchy includes: chemical or hazard source substitution, engineering, administrative, and personal protective equipment (PPE). In theory, PPE should only be used as a temporary measure until a permanent alternative can be employed.²⁴ However, many “feasible alternatives” are not practical due to cost, technology, or performance limitations. Therefore, the “temporary” PPE becomes the primary and sometimes only line of defense against occupational exposures.

Aside from airborne exposure to occupational and environmental contaminants, BEs are also tasked with monitoring drinking water systems to ensure the supply is safe to drink and that contaminants are below regulatory limits. The U.S. Environmental Protection Agency (EPA) has established and enforces contaminant limits for 87 primary contaminants in 6 categories.²⁵ In addition to the primary contaminants enforced, the EPA initiated the Unregulated Contaminant Monitoring (UCM) Program in 1988 that will last through 2016 with the purpose of assessing the prevalence of 169 unregulated, potentially hazardous contaminants that may require monitoring in the future.²⁶

While hazardous workplace chemicals are the most obvious type of exposure assessed for health risk determination, there are numerous types of exposures that must be assessed by BEs. Although typical exposures originate from within the workplace, exposures from the ambient air, water supply, facilities adjacent to installations, from accidents, and deliberate actions must also be assessed. Because of this variance in hazard type, BEs must be prepared to monitor for a wide variety of hazards to include: chemical, ionizing and non-ionizing radiation, biological, noise, thermal stress, and ergonomics. In an emergency response role, BEs must also be ready to respond to unknown hazards; collect, identify, and quantify exposures; make recommendations to mitigate further exposure; and provide a health risk assessment among varying exposure groups (i.e. responders, casualties, and downwind personnel).

Bioenvironmental Engineering Occupational and Environmental Monitoring Capabilities

Bioenvironmental Engineering (BE) monitoring capabilities are separated into two distinct classes of detection: field monitoring and laboratory analysis. Field monitoring is conducted on location by BE technicians and provides results with little to none processing after collection. This type of exposure monitoring is further delineated into monitoring in true real-time and monitoring with delayed results (24-48 hours). Monitoring in both of these classes either provide a quantitative or a qualitative result and are typically used for screening purposes to determine if follow-on laboratory analysis is needed or during emergency response scenarios. The only areas where field response equipment is used for regulatory compliance are in a limited number of water quality parameters (bacteria, pH, and chlorine levels), radiological, noise, and heat stress. Aside from water quality monitoring, biological monitoring is only conducted by BE in emergency response and a screened sample must always be sent for further laboratory confirmation, if the field screening result indicates a positive determination. Laboratory analysis

is very robust in the area of chemical analysis and has an advantage over field detection in its level of precision and accuracy obtained. Laboratory sampling is used for compliance monitoring requirements and involves the analysis of exposure levels determined by air and water samples collected in the field. After collection, they are subsequently packaged, preserved, and shipped for analysis to determine occupational exposure.

Field Monitoring Capabilities

Bioenvironmental Engineers (BE) maintain approximately 30 separate pieces of field exposure monitoring equipment with slight variance from base-to-base depending upon the unique exposures associated with the specific mission of the base. For example, a depot maintenance base BE flight may have a more robust capability for detecting exposures within the industrial hygiene area of detection while a BE flight at a base with nuclear munitions will have a more robust detection suite for radiological hazards. Appendix A illustrates the diversity of BE field monitoring detection equipment separated by class, type, and technology that BE personnel are required to maintain proficiency in.

Of the BE equipment on-hand, only 9 pieces of equipment conduct true, real-time monitoring. For the purpose of this evaluation, real-time monitoring was considered an exposure measurement within at least one minute of collection. 11 other pieces of equipment possess the capability of delayed detection, where results of the exposure can be acquired within 24-48 hours. As evident in Appendix A, this distribution is not equal among the detection classes and the majority of real-time detectors are in the area of radiological and physical exposures. While these classes are important in an occupational setting, a significant gap exists for the detection of chemical and biological hazards. This means that evaluation of these exposures must involve the collection and shipment of samples for laboratory analysis. The overall impact of this shortfall is

that occupational overexposures may go undetected due to a limitation in resources and budgeting; laboratory analysis is not free.

Although field screening analytical tools are a necessity, they do possess drawbacks in terms of analysis. One area that does not easily stand out is the burden placed upon the BE technician responsible for collecting the data. Each of the 30 separate pieces of equipment all require a unique proficiency to operate; they require periodic maintenance, calibration, operational checks, pre-calibration, and post-calibration procedures. Due to the sheer volume, proficiency of each piece of equipment becomes diluted and ultimately the detection proficiency and confidence in sampling results suffers. The only “ticket” type detectors in the BE inventory are passive samplers that detectors do not provide instantaneous readings of an exposure. Usually they are an absorbent or adsorbent media that collects the hazard of concern equivalent to the exposure of the individual wearing it; after the duration of the monitoring period, the samples are collected and shipped for analysis. Other dosimeter type recording instruments allow for the detection of radiation and noise exposures; only radiation exposure detectors have the ability to provide instantaneous alarm to an individual if they are overexposed in terms of total dose or dose rate.

Laboratory Analysis Capabilities

The United States Air Force School of Aerospace Medicine (USAFSAM) Lab divides sampling and analysis into three separate sections: occupational health (industrial hygiene), environmental health, and radiation.²⁷ The occupational health analytical services analyze samples in the following detection categories: gas chromatography (five sub-classes), inductively coupled plasma (two sub-classes), high performance liquid chromatography (two sub-classes), ion chromatography, and gravimetric analysis.²⁸ The environmental health services analyze

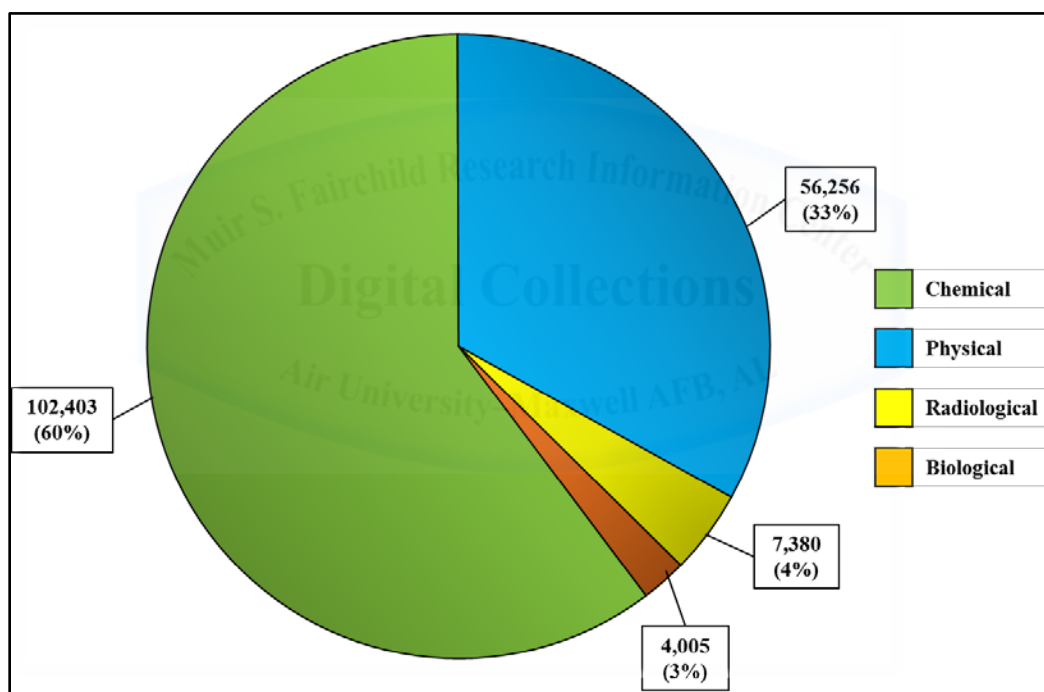
samples in eight separate classes that cover air, water, and soil mediums.²⁹ The primary environmental analytical service employed by Bioenvironmental Engineers is drinking water. Radiological analytical services are separated into five detection areas: gamma spectroscopy, alpha spectroscopy, gross alpha/beta counting, liquid scintillation counting (LSC), and inductively coupled plasma mass spectroscopy (ICP-MS).³⁰ The USAFSAM lab is accredited and capable of analyzing 95 standardized methods from the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), and the Environmental Protection Agency (EPA) for occupational, environmental, and radiological samples.³¹

Prevalence of Occupational and Environmental Exposures in the Air Force

Exposure monitoring conducted by Bioenvironmental Engineers (BEs) are divided into two broad categories: occupational and environmental. The majority of occupational exposures are measured through air sample collection and analysis of contaminants for chemical and particulate inhalational exposures. Measurements of physical exposures are also monitored to include noise, temperature, and radiation. The primary environmental exposures monitored by BEs are in drinking water; other environmental sampling includes atmospheric monitoring for ambient outdoor or indoor air quality (IAQ) concerns. Regional data of environmental air quality available publicly from external weather or environmental agencies and relevant to the installation are also assessed and documented. Monitoring for potential hazards to the base population from hazardous sources, such as factories or chemical storage areas, originating from within or in close enough proximity to the base that they may be a potential health threat are also assessed.

Air Force occupational and environmental exposures are documented in the Defense Occupational and Environmental Health Readiness System (DOEHRS) as required by Department of Defense and Air Force regulations.³² As of 31 July 2015, there were a total of 170,044 instances of 1,497 hazards were identified within 77 common industrial processes in the system across 188 Air Force locations (including Active, Guard, Reserve, and Deployed locations).³³ Figure 1 depicts the distribution of hazards among the chemical, physical, radiological, and biological hazard classes.

Figure 1. Hazard Prevalence by Class across Air Force Installations



As can be seen, the chemical and physical hazard classes account for 93% of all hazards. Further analysis was performed on each class to determine the most prevalent, specific hazard within each category. Appendix B depicts the top 50 most prevalent hazards across all hazard classes. In addition, the number of Air Force installations and common process categories the hazard is present in is also displayed. These two values are important to understand just how wide spread particular hazards are. Some hazards are always present in very common Air Force

processes (i.e. jet fuel in a refueling process), while other hazards are only present in isolated and unique processes on only a handful of Air Force installations. Other hazards span multiple common process types, such as noise and physical hazards. These three parameters are very strong indicators of just how much of a systemic threat each of the particular hazards may be. Of the 1,498 unique hazards identified in DOEHRS, the top 50 listed represent roughly 82% of all hazards identified.³⁴

An Explanation of Focus on Chemical Hazards

Physical hazards include noise, temperatures, ergonomic, and kinetic sub-categories. Although physical hazards account for a large percentage of hazards, they were not the focus of research review because present day instrumentation offers a real-time monitoring capability for most of these types of hazards. While these hazards were not the primary focus of literature review, any study or news article discovered that was related to nanotechnology detection of these hazards were documented.

Some of the current noise and thermal stress (temperature) measurement systems offer a relatively easy and real-time monitoring capability, however, a less intrusive and permanently affixed system would benefit personnel by immediately alerting them to hazardous conditions. Noise hazards are acoustically measured by assessing the average amount of decibels (dBA) a worker is exposed to and should not exceed 85 dBA. While it is not explicitly stated in regulatory guidance, noise dosimetry usually involves the collection of noise data sampling over a period of three work periods or three workers assessed simultaneously over the period of one work shift.³⁵

Thermal stress monitoring assesses ambient air temperature, radiant temperature, air speed, and absolute humidity which is used to calculate flag conditions and corresponding work-

rest cycles to reduce the risk of thermal injury.³⁶ While this practice is beneficial at reducing injuries, a direct temperature monitoring system for each individual worker that would alarm if temperature thresholds are exceeded would be ideal.

Ergonomic hazards are quantified based upon worker movement, exertion, repetition, vibration, or weight of items manipulated in a process and are simply defined by OSHA as the study of work and movement to reduce musculoskeletal disorders (MSDs).³⁷ A monitoring device for ergonomic hazards would not be feasible as there currently are no exposure limits established, only assessments of risk associated with a process.

The confined space “hazard” is actually an area which is defined by OSHA as a space that is not meant for occupancy, but are large enough for people to enter to perform certain tasks.³⁸ Hazards contained within these areas usually fall in another sub-class of hazards, however, the confined space acts with a synergistic effect that increases the overall risk of injury to the worker. Jet Fuel, commonly called JP-8 or Kerosene, and hydrogen sulfide, H₂S, are common chemical hazards found within confined spaces on Air Force installations. Any confined space that has potential to contain a hazardous atmosphere, material that could engulf an entrant, or tapering walls or floors that could trap or asphyxiate an occupant is considered a “permit-required confined space.”³⁹

Kinetic hazards are, for the most part, assessed by Wing Safety or Fire Departments and include a wide range of hazards ranging from slips, trips, and falls to hot objects, or cuts from sharp objects. The current state of BE monitoring capabilities forces a tough decision to be made for hazard analysis: they can be screened with field monitoring equipment if the hazard meets the detection criteria and the survey may not even meet regulatory compliance, or they can be sampled using tedious regulatory protocols and shipped to a lab for analysis at a cost, and lastly

the flight can attempt to model the potential exposure to occupational hazards and determine an exposure assessment based upon “professional judgment”.

Literature Review

Gold Nanoparticle Properties

A nanoparticle is defined as an “ultrafine unit with dimensions measured in nanometers (10^{-9}).”⁴⁰ Nanotechnology is an extremely broad and highly diverse area of study. Gold nanoparticles (AuNP) represent just one of numerous types of nano-scale detection platforms and is a highly versatile medium for numerous detection technologies. Literature review in this report will focus on the research areas of airborne and aqueous hazard detection research efforts that are most applicable and beneficial to the current Bioenvironmental Engineering (BE) career field detection limitations. The diversity of research and the applicability of gold nanoparticle detection technology is clearly seen when the sheer amount of research is reviewed. Although gold nanoparticles were the primary focus, other nanoparticle platforms were also considered if they possessed applicability to BE monitoring requirements.

Optical (Colorimetric) Detection of Water Contaminants

When visualizing gold, its property of brilliant yellow, metallic luster often comes to mind. Contrarily, colloidal gold in solution exhibits a range of color in direct correlation to particulate size.⁴¹ The colors produced range from deep red to a pale blue as particle size increases and is also influenced by particle concentration and shape within the solution.⁴² This colorimetric property of gold is important in the assessment of gold nanoparticles (AuNP) as a potential replacement for current detection methods contaminants in drinking water. A common detection platform used by Bioenvironmental Engineering (BE) technicians across the Air Force

for screening of water contaminants is a UV-Visible Spectrophotometer. Sample analysis begins by first adding a reagent to a set sample volume and allowing for a reaction to take place. After a pre-determined amount of time elapses for the reaction to occur based upon the analysis method being employed, the sample is then placed into a chamber on the unit and a reading is displayed. This technology is based upon the absorbance of specific wavelengths being measured; the percent of wavelength transmitted from source to receiver through the sample is inversely proportional to the amount of contaminant present in the sample.⁴³ Although the analysis is simplistic in nature, there are some significant drawbacks to the technology.

Analysis of a Hach DR 6000™ UV-VIS Spectrophotometer, one of the latest models from a well-established detection company, sheds some insight on the capabilities. The unit offers the capability to detect 66 separate contaminants using 180 distinct detection methods.⁴⁴ Of those methods listed, only 47 are US EPA certified sample protocols that can be used for compliance sampling.⁴⁵ Furthermore, each of the sample protocols are only valid for a specified range of concentration and each reagent for each method must be purchased separately and has a specified expiration date.⁴⁶

Colorimetric detection of contaminants enhanced with gold nanoparticles have shown promising and superior results in comparison to spectroscopy alone. In one study, researchers reported successful detection of DNA, small molecules, proteins, and ions by attaching gold nanoparticles to polymers that only interact with target compounds.⁴⁷ This lock-and-key interaction produces a visible color change in solution that can be seen with the naked eye.⁴⁸ When this technology was combined with a UV-Visible spectrophotometer, researchers were able to detect contaminants down to the pico (10^{-15}) and femto (10^{-18}) range.⁴⁹

Interference of other contaminants within a sample is also in issue in current UV-Vis and colorimetric monitoring systems. In order to obtain a measurement, a reagent is added to a sample. The resulting reaction product formed is then measured in direct correlation to the amount of target contaminant in the sample. However, if other contaminants are present that are also susceptible to reacting with the reagent added, results may be skewed and inaccurate. In another study, the selectivity of a silver-gold nanoparticle aggregates demonstrated a high selectivity for nitrites even in the presence of 25 other contaminants.⁵⁰ This study demonstrated the ability to detect the presence of the nitrite ion in a sample by the naked eye down to 1.0 μM (micro molar) concentrations and as low as 0.1 μM when analyzed with UV-Visible Spectroscopy.⁵¹

Although colorimetric detection may not be applicable for all types of water contaminants, the versatility gold nanoparticles and the breadth of research is portrayed in a review of water monitoring method studies that took place between 2007 and 2009.⁵² A total of 25 different studies using gold nanoparticles to detect 8 different contaminants were assessed.⁵³ A unique property of gold that adds to its versatility is its ability to easily bond with the sulfur atom of a thiol group.⁵⁴ Once bonded, the thiol group serves as a binder between the nanoparticle and a functional group attached to the opposite end of the thiol group that would interact with a target compound.⁵⁵ This molecular combination of thiol and functional group is known as a “ligand” that is attached to the gold nanoparticle and has been successfully used to detect heavy metals, aromatics, organophosphates, toxins, and biological agents in water.⁵⁶ The end result of the interaction with nanoparticle and target compound is either a color change that can be viewed with the naked eye or a UV-Vis spectrophotometer or an electrochemical change that sends a signal with an intensity correlated to the concentration of contaminant.⁵⁷

Colorimetric detection using AuNPs has also shown the ability to be used for contaminants that are conventionally difficult to detect due to the equipment required or interference by interactions with other contaminants in a sample.⁵⁸ Lanthanide, a contaminant known to be difficult to detect, was used as a target ion for detection in a study; malonamide was successfully attached to an AuNP base and the subsequent aggregation observed in the presence of lanthanide ions allowed for a measurable colorimetric change corresponding to the concentration of ions in solution.⁵⁹ The study also showed that there was minimal aggregation observed when tested in solutions with other metallic ions showing a selectivity towards the lanthanide ion.⁶⁰

Electrochemical Detection of Water Contaminants

Another method of detection harnessing gold nanoparticles (AuNP) involves the coating of a film or plate with modified nanoparticles designed to detect specific target compounds. They are arranged in a manner that produces or interrupts an electrical signal as the nanoparticles interact with the compounds; the resulting signal change measured corresponds to a quantifiable amount of contaminant present.

In a study, thiol functionalized AuNPs were placed onto a silica film electrode surface in a sorbent array known as Self-Assembled Monolayers on Mesoporous Supports (SAMMS).⁶¹ This novel approach by Pacific Northwest National Laboratory combined SAMMS with a detection technology known as Square Wave Anodic Stripping Voltammetry (SWASV) to detect mercury, lead, and actinide contaminants in aqueous solution.⁶² Although this experimental research failed to deliver conclusive results in quantification, it did bring to light the potential applicability of this technology as a reusable sensor platform and one with a high degree of selectivity among other contaminants in solution⁶³.

Another seemingly more successful platform that has been reported as an effective electrochemical sensor involves the use of molecularly imprinted polymers (MIP) on nanoporous gold leaf (NPGL).⁶⁴ Yingchun Li and colleagues conducted research on the detection of metronidazole (MNZ) using NPGL that had been molecularly imprinted with MNZ.⁶⁵ Results under varying pH conditions were evaluated and detection sensitivity was reported in the 10^{-11} mol per liter range.⁶⁶ This research was compared to conventional high-performance liquid chromatography (HPLC) analysis as a reference method; the results indicated that it was “valid for real sample analysis”.⁶⁷ This nuance seems to imply that the platform developed could be used in place of HPLC detection with better results.

This study reiterates the versatility of AuNPs; MIP technology essentially imprints the target compound repetitively onto an array of AuNPs. When the target molecule interacts with the MIP array, a signal change is produced. Because the array is specifically tailored to the compound, it is extremely selective and allows for a very high degree of sensitivity. Furthermore, since target molecules are used in the manufacturing process to imprint a mold on the electrochemical surface, there is very little room for error.

Detection of Volatile Organic Compounds (VOCs)

Detection of VOCs is by far one of the most challenging aspects of exposure monitoring for Bioenvironmental Engineering technicians simply because there are so many different variants of VOCs within the numerous functional classes of compounds. Research conducted by Hadi AlQahtani at the University of Sheffield using thin films of gold nanoparticle dodecanethiol core/shells demonstrated the ability to detect the alkane class (pentane, hexane, etc.) of VOCs with selectivity and sensitivity at normal room temperatures.⁶⁸ The alkanes functioned as a form of resistance in a circuit, causing the dodecane shells to swell leading to a

change in voltage and ultimately a quantifiable signal.⁶⁹ Although this method works, there were some issues reported with interference from alcohols, ketones, and water.⁷⁰ However, the benefits and applicability of this platform reported included the ability of the process to be completely reversible and it also reported detection limits down to 15 ppm.⁷¹

In a separate experiment, conducted by Niti Garg and a joint team from Carnegie Mellon University and the National Institute of Occupational Health and Safety (NIOSH), attempts were made to overcome some of the current shortfalls of monothiol capped gold nanoparticle detection systems by instead using a trithiol capped system.⁷² Their efforts were aimed at addressing issues of stability over long periods of time that had been observed in previous research.⁷³ It was presumed that the destabilization of the nanoparticles over time were directly correlated to the precision of results obtained.⁷⁴ The experiment tested the ability of trithiol ligand variants versus the monothiol ligand AuNPs to detect toluene, ethanol, dichloromethane, methane, and acetone.⁷⁵ Results showed that the trithiol variants were comparative to the monothiols and in some cases even more sensitive to test analytes. More importantly, they still performed with less than 10% degradation after a period of 6 months compared to a 47% degradation of the monothiol variant⁷⁶.

Tisch and Haick from the Israel Institute of Technology modified an array of chemisensitive monolayer-capped metallic nanoparticles (MCNP) to successfully develop a prototype detection system with a focus on breath analysis. By harnessing MCNP chemiresistive films within sensor arrays, the researchers were able to yield results with very advantageous properties.⁷⁷ The chemiresistor design of the thin layer structure allowed for the ability to control the geometry of the nanoparticle arrangement that had a direct impact on the interaction quality of the analytes.⁷⁸ This study involved the use of a cubically arranged MCNP

array that they believe allowed for more swelling in the structure once it came in contact with the target analyte. The consequential change in voltage corresponds to a quantifiable number with a higher degree of sensitivity compared to conventional spherical arrangements.⁷⁹ Another benefit cited was that multiple ligands could be attached and each interacted with a unique analyte allowing for the ability to detect multiple contaminants; this allowed for varying responsiveness of certain contaminants based upon the type of ligand attached to the MCNP array.⁸⁰ In short this meant that one manufactured nanodetection platform could potentially detect multiple hazards.

The study went on further to discuss potential arrangements for detecting disease states of patients based upon the type of VOC's detected in the sample and proved the possibility that one sensor platform could be designed with the ability of detecting multiple contaminants, simultaneously.⁸¹ Areas noted requiring further research included the ability of the detection system to detect contaminants consistently in atmospheres of varying humidity, temperature, and contamination levels.⁸²

Detection of Gasses

This portion of the review focused on research efforts being made towards the detection of gasses. Unlike VOCs, gasses are considered inorganic (not containing carbon) and can contain diatomic (H₂, O₂, etc.) or molecular compounds. Certain types of gasses can be very difficult to detect as they are inert (non-reactive) but may still pose a health hazard to industrial workers.

The U.S. Naval Research Laboratory, successfully detected nitrogen dioxide and ammonia down to the 10 parts per billion range using an array of silicon nanowires capped with an electrode.⁸³ The experimental data factored in humidity at an approximate 30% range and

interestingly enough, the increased humidity resulted in better detection performance of the sensor at very low concentrations.⁸⁴ The report further detailed the synthesis process was not time consuming, did not require specialized equipment, and yielded fast response times.⁸⁵

Detection of Airborne Metals

Contrary to the other forms of detection already evaluated, the detection of metallic compounds in air may prove somewhat more difficult using nanoparticle detection technology. This is due to the fact that airborne metals must be physically manipulated in order to be aerosolized. In an industrial setting this is usually caused by a process involving manipulating a metallic surface such as sanding, grinding, or sandblasting. Furthermore, the metal may not be present in pure form, but rather bonded to another atom or molecule, but still hazardous once inhaled. Current detection methods overcome this issue by digesting a collected sample in an acidified solution to liberate the metal. Once dissolved, the metal ion can then be analyzed similar to metallic contaminants in water samples.

Research into nanotechnology studies conducted to detect metallic compounds was very limited. Although not based upon nanotechnology detection, there were a few articles that reported detection methods that may serve as a more advantageous alternative to current laboratory methods. One study involved the conventional collection of metal particulates through an air capture filtration method.⁸⁶ The sample collected was then placed onto a microfluidic paper-based analytical device (micro-PAD) and the metals were wicked into contact with impregnated chemicals; the subsequent colorimetric change corresponded to quantitative values of various metal contaminants detected.⁸⁷ The end result was the detection of metal contaminants in a matter of minutes versus the approximately 3 week conventional turn around for lab samples; detection of iron, copper, and nickel were assessed, however, no

specific level of quantification was reported further than “levels relevant to human health.”⁸⁸

Other experimental results for detection of airborne metals involved the use of high energy sparks⁸⁹ and laser based analysis systems.⁹⁰

Detection of Biological Pathogens

Research into the use of nanoparticles for the detection of biological agents is quite robust and further highlights the cross-organizational interest into this field of study.

Applications vary from the detection of pharmaceuticals and metabolites to contaminants causing foodborne illness and other varying areas of medical care. While the biological detection capabilities of the BE career field are probably the least developed, they play a critical role in the regulatory monitoring of bacteriological contaminants in drinking water systems as well as the field screening detection of Biological Warfare Agents (BWAs).

Monopolizing on the colorimetric properties of AuNP nanoparticle suspensions, researchers at Air Force Research Laboratory were able to successfully detect concentrations of riboflavin in-vitro.⁹¹ The study involved the use of aptamers, peptide molecules that bind to specific areas, of varying lengths linked to gold nanoparticles by means of a thiol ligand bond.⁹² In the presence of varying environmental parameters and levels of potential interferences, the riboflavin-bonded AuNPs were able to detect (by aggregation) the free riboflavin in the micromolar range with a degree of correlation.

The conductive properties of gold were showcased in a separate study by Electronic Bio Sciences, LLC.⁹³ This AFRL funded study developed a method of monitoring the interaction of gold layered nanotube sheets with DNA containing a predetermined functional group.⁹⁴ These specific DNA groups served as circuit breakers when interfacing with the nanosheets. This

added resistance created a drop in voltage current and produced a corresponding quantification level.⁹⁵

Surface-Enhanced Raman Spectroscopy (SERS) augmented by silver nanoparticles also has applicability in the area of biological detection. In a study performed by the Naval Medical Research Unit San Antonio, 16 separate bacterial isolates were tested on an array of silver nanorods and evaluated.⁹⁶ Successful identification was made for all 16 pathogens in a matter of 15-30 seconds.⁹⁷ The results of the evaluation were validated using conventional quantitative polymerase chain reaction (qPCR) that verified the "molecular fingerprints" for each agent in detected by the SERS platform.⁹⁸ While specific sensitivity was not discussed in the results of this experiment, they were described as quantifiable and detection of the bacterial agents was significantly faster than the present day "gold standard" technique for bacterial analysis, all while using a handheld portable Raman Spectroscopy system.⁹⁹

In a summary article specifically addressing the detection of cancer cells using nanotechnology, Mauro Ferrari presented an in-depth assessment of the current status of nanotechnology detection systems at that time.¹⁰⁰ While his article is mainly focused on detection platforms for cancer detection and treatment, his depiction of the detection technologies crossed all chemical classes.¹⁰¹ Along with the nanowire type electrochemical reaction platforms discussed, Ferrari also addressed the nanocantilever detection platform for the detection of cancerous and precancerous tumor biomarkers.¹⁰² This array type contains numerous finger-like cantilevers with varying antibodies attached; when the corresponding antibody interacts with the biomarkers, a circuit disruption is created and a change in electrical signal results.¹⁰³ At the time of the article, in 2004, Ferrari stated that there was little advantage in terms of detection sensitivity compared current methods, however, he did go on to discuss

how very realistic it would be to have an array of “several thousand sensors” on a single microchip.¹⁰⁴

Detection of Physical Hazards

In a 2012 report in Physical Review Letters, a team of researchers demonstrated the ability of “optically trapped” single gold nanoparticle to detect acoustic vibrations in liquid media at levels down to -60 decibels.¹⁰⁵ A visual comparator would be to imagine a small ping-pong ball in a fully enclosed container with bass applied to it; the detected vibrations of the ball in response would correspond to the level of noise present. The detection method employed a Fourier transformation analysis of the motion of the trapped nanoparticle and the results revealed that not only could the gold nanoparticle detect sounds at extremely low levels, it could also locate the direction of the sound source.¹⁰⁶

Current heat stress methods involve collecting atmospheric temperatures to develop a corresponding work-rest cycle dependent upon factors of ambient temperature, radiant heat, and humidity. Research into thermal sensors placed directly on individuals provided real-time monitoring of skin temperature with a high level of sensitivity and fast response time.¹⁰⁷ These interconnected filamentary arrays were a non-invasive alternative that provided a high degree of elasticity; the result was very little discomfort by the wearer and a secured contact to skin surface.¹⁰⁸

Detection of Radiological Hazards

Conventional radiological detection instrumentation harness various technologies. Ion chambers, Geiger-Mueller, and crystal scintillation are three of the main categories of current detection. One of the most beneficial involves the use of crystal scintillation to detect various

energy levels that are uniquely produced corresponding to the radioactive isotope present. A Georgia Tech Research Institute study explained the prospect of using quantum dot nanotechnology as an alternative to conventional scintillation technology.¹⁰⁹ Little further was divulged aside from the fact that this technology is still in development and analytical results have yet to be published.¹¹⁰

Existing Nanotechnology Detection Platforms

A review of the latest commercially available nanotechnology based detection platforms revealed a common theme; the majority of articles and systems reviewed pertained to the detection of biological pathogens, metabolites, cancer treatment, or other closely related genres. While some articles were accurate in the results reported, care was needed in this section of review as other breaking news articles touted as full-blown systems turned out to be no more than a sensational report on a recently published research results.

In one such article published on nanowerk.com on 30 September 2015, a report was given detailing an improved detection sensor to detect cancer simply by analyzing an individual's breath.¹¹¹ This news was actually coverage of an American Chemical Society (ACS) publication detailing the results of a recent AuNP research project.¹¹² Although this was not quite a system, the results of the experiment reported an 82 percent accuracy rate in detecting ovarian cancer in 43 volunteers; 14 of the 17 volunteers with cancer were accurately assessed by a non-invasive, ticket-based system.¹¹³

Another article published by Mingo Pu on Nanotechnology Now drew attention to what appeared to be their very own research into the discovery of a more natural way of structuring nanowires to improve the efficiency of the manufacturing process.¹¹⁴ Further explanation of the article described the “catenary” structure discovered was one that was a “free-hanging chain

assumes under its own weight” and an example provided was that of a spider’s web.¹¹⁵ The breakthrough reported was that this catenary structure overcame resonance experienced in other discrete nanostructures which would allow for greater bandwidth in optical nanostructures.¹¹⁶

The website Phys.org covered an actual sensor system from VAPORSENS detailing their plans to build a handheld sensor prototype by the end of 2014.¹¹⁷ A visit to the VAPORSENS homepage revealed an elaborate overview of “vSENS electronic nose technology” that reported detection down to the parts per trillion level within seconds for different chemicals that would be available for purchase in the 4th quarter of 2015.¹¹⁸ The product page listed 40 chemicals in 6 separate areas; correlation to the hazards classes presented in the paper fall into the inorganic and organic chemical classes.¹¹⁹ The technology page of the website equated the nanofiber technology to that of the “olfactory cilia of a dog’s nose” and depicted the sensor’s performance in comparison to other sensors configured in a chip-based chemiresistor array.¹²⁰

Another chip-based platform was showcased in an article on sciencedaily.com which referred to a research report published 25 September 2015 in Nature Scientific Reports.¹²¹ The device was specifically designed for the detection of the Ebola virus and used optical detection nanotechnology.¹²² The results reported excellent specificity with zero false positive when tested against two other virus strains while also delivering sensitivity results comparable to polymerase chain reaction analysis that is the current gold standard for laboratory analysis of biological pathogens.¹²³

The Argentinian Ministry of Science, Technology, and Productive Innovation reported on a device developed with a roughly \$13 million dollar grant that could directly detect various diseases in blood in just 15 minutes, powered only by solar or universal serial bus (USB),

without the need for cultures or a lab.¹²⁴ Unique to this article, the cost per unit was also discussed and quoted at approximately \$1,000.¹²⁵ In-depth discussion on the underlying technology was not provided further than an explanation that it involved the use of “electrochemical transduction” producing a signal from the “antigen-antibody complex” interaction.¹²⁶ Aside from blood samples, the article also explained that this technology could further detect biological diseases in samples of milk as well.¹²⁷

Conclusions

Conclusions made from the evaluation of current nanotechnology in the literature review section assess the results of the review against the research criteria established. The emergence of any trends identified during the course of the review and any benefits or drawbacks found will be discussed further. Four main conclusions were drawn from the review and each are expounded upon in their corresponding section.

Conclusion #1 - Nanodetection Technology Does Not Meet All Evaluation Criteria

Many of the research articles evaluated met some of the research criteria, however, no single platform assessed met every component of the criteria established. As more research was reviewed, a distinct area of focus by researchers was recognized. A large majority of research being developed is for the biological, medical, and military fields. Many of the articles assessed were aimed at efforts other than for the improvement of occupational health exposure monitoring. In particular, detection of biological agents and volatile organic compounds related to explosives and chemical warfare agents are being heavily researched. Very little was discovered for the detection of airborne metals, physical, or radiological hazards. The detection technology for water contaminants seemed to benefit from the aqueous nature of biological

systems and contained quite a few reports on new detection methods. Each technology type reviewed contained its own set of benefits and drawbacks that will be discussed and compared to the existing platforms in the following sections. Appendix C provides an overview of the research reviewed during this evaluation and corresponding results. Only the evaluation criteria specifically addressed in the reports were annotated.

Conclusion #2 - Two Broad Nanotechnology Classes – Optical and Electrochemical

Two broad categories of nanotechnology emerged during the assessment. Most research reviewed involved variations of either the use of gold nanoparticle's colorimetric properties or its ability to attach analyte-specific ligands in a film, tube, or electrode configuration that creates a change in electrical current when interaction occurs. The majority of the research reviewed involved the use of gold nanoparticles, however, some studies used other nanotechnology platforms including silver, graphene, and copper. Only a few reports on the detection of physical hazards were discovered and assessed during this study; no research into the detection of radiological hazards using nanotechnology detection was discovered during the research review aside from a brief report on the use of quantum dot technology to replace crystal scintillation.

Conclusion #3 – Benefits and Limitations of Each Class

Each category displayed unique trends; studies into optical nanotechnology were more focused on the detection of water contaminants while the electrochemical class of research had more focus on airborne contaminants. Both classes reported success in sensitivity and selectivity, however, performance in varied environments (i.e. humidity, temperature, pH) seemed to be exclusive to the electrochemical class. The optical detection class possessed a distinct advantage over electrochemical due to its ability to augment the existing technology of

UV-Visible light spectroscopy. The electrochemical class displayed the unique ability of being able to detect multiple hazards simultaneously. Detection of inorganic metals was strictly confined to contaminants in an aqueous environment while the detection of inorganic gasses was almost exclusively limited to the electrochemical detection class. The number of studies conducted on the detection of biological agents was roughly even between the two classes and both reported very successful results for the detection of specific pathogens.

Recommendations

From the research reviewed that has been conducted within this field, it is obvious that the benefits of successfully harnessing this technology are widely sought. However, work is still needed to fine tune any proposed detection platform into one that would meet the criteria established. In order to do so, a system must be able to demonstrate a level of precision and accuracy that is presently only seen in lab settings while also possessing the convenience and quickness of field screening tests. All nanotechnology classes reviewed reported a very low limit of detection for the target hazards, however, issues of interference with other contaminants present and the level of precision the platform can achieve must still be resolved before they would be deemed acceptable by regulatory agencies for compliance sampling.

Recommendation #1 - Enhance UV-Vis Spectroscopy with Nanotechnology

The use of nanotechnology as a replacement for current colorimetric detection systems appears to be a very viable option and would replace the need for spectrophotometry measurements. Furthermore, with this technology, technicians may be able to measure levels of sensitivity current UV-Vis spectrophotometer provides with the naked eye alone. If nanotechnology was used as an amplification to current UV-Vis analysis, technicians in the

field may also be able to collect samples acceptable by EPA standards that would eliminate the need for costly and timely laboratory analysis.

One very beneficial result of this technology is the ability it could grant the Bioenvironmental Engineering career field in terms of monitoring for biological agents. Currently, capability is only limited to only 8-10 biological warfare agents; nanoparticle technology would allow for a much more diverse range of biological agents that could also be applied to measurements in drinking water.¹²⁸ This would greatly reduce the workload and cost requirement of bacterial analysis that is required by the EPA for public drinking water. Current analysis method requires the collection of a sample, a blank, and an incubation period of 24-48 hours. Furthermore, the results for this analysis are qualitative. Colilert™ is a typical sampling system used by BEs in the career field. These vials will turn a faint to dark yellow if coliform bacteria is present in a water sample and will fluoresce under a black light if fecal coliform is detected.

Recommendation #2 - Further Develop Microelectrode Detection Technology

Microelectrode detection systems show an advantage over colorimetric systems in terms of reversibility. The chip or circuit dedicated to the detection of a single contaminant could be reused in a detection unit multiple times. Due to the minimum size of the sensor, it opens up the possibility of an array assembly where one sample could be placed into a detection system and analyzed for multiple contaminants simultaneously and reversibly. Research results have proven the ability to detect multiple contaminants simultaneously, however, the class of chemicals detected, environmental factors, and other interferences are current shortfalls that need to be improved upon. Although microelectrode assembly research has been shown to be a reversible and reusable interaction, researchers have encountered difficulty in developing a truly

reversible process where all functionalized groups release the target molecule in preparation for a new analysis on a different sample and then redetect with the same level of performance.

Recommendation #3 – Validate the Performance of MIP Technology

Molecularly imprinted polymer (MIP) technology combined with nanoporous gold leaf (NPGL) appeared to be one of the most successful platforms reviewed. It is a very promising method of manufacturing a platform to detect the greatest diversity of analytes. The reason being is that the target molecule is used in the manufacturing process. This leftover “shell” is then applied to a surface and triggers an electrical change when the target molecule makes contact with the shell. This allows for a very unique and highly selective interaction which enhances the system accuracy. Use of MIP platforms show exceptional promise for selectivity, however, the manufacturing process requires the actual imprinting of the target compound into a gold “shell”. This means that for every contaminant system developed, a different synthesis will be required that will incur costs, unless detection systems can be developed that imprint multiple analytes within the same array.

Recommendation #4 – A Hybrid Platform for Airborne Metals

In order to maximize the benefits of nanotechnology detection, the Bioenvironmental Engineering career field should consider a hybridized detection platform. There is a significant gap in efforts being made to enhance the detection capabilities of airborne metallic compounds that account for 24% of the 50 most prevalent hazards listed in Appendix B. It is presumed that one of the challenges to overcome in order to detect airborne metal particulates with nanotechnology is for the particulates to present themselves on an atomic or molecular level. Metallic dusts are not generated homogeneously in an occupational setting and become airborne

by some form of mechanical manipulation such as sanding, grinding, or spraying. This results in particulates generated heterogeneously that are comprised of multiple atoms or molecules conglomerated into massed particulates. A one-on-one interface between the analyte and ligands attached to the nanoparticle, nanocircuit, electrode, or wire is required to create a signal and corresponding quantification, which does not occur with massed particulates.

Since detectors have been developed for aqueous metallic contaminants, an impingement device should be considered to allow for this interaction and subsequent detection to occur. A method proposed for further exploration would involve collecting an air sample and injecting it into an acidified water reservoir that would allow for any metallic particulates to dissolve into solution. Afterwards, the electrochemical, optical, or a combination of the two types of sensors could detect the dissolved particulates in the required manner. The sensors could be placed into the same chamber if it possesses the ability to detect at the pH level present or the solution could be neutralized or buffered prior to passing into a detection chamber where the sensors would be located. Although this is not ideal, if this type of analysis could provide lab quality, regulatory compliant results it would be well worth it.

Overall Recommendation

Although the results do not seem to provide all of the answers at face value, augmentation of nanosensors with existing technology makes a portable detection strip placed on a worker very feasible. Detection platforms already exist employing this type of technology and as research into these fields of study progress further, their performance will only improve. The results offered by current nanotechnology research effort may not resolve all of the detection shortfalls that BEs are currently experiencing in the career field, however, if the feasibility is not explored further it may be an opportunity sorely missed.

Conclusion

The current state of Bioenvironmental Engineering detection capabilities and requirements creates significant challenges. Nanotechnology detection platforms were evaluated as a potential alternative to present day laboratory and field detection methods for the assessment of occupational and environmental exposures from contaminants present in the air and water. Based upon the research evaluated, nanotechnology sensors in their present state do not meet all of the evaluation criteria established. However, many of the platforms reviewed in the two broad categories of electrochemical and optical nanosensors met some of the evaluation criteria parameters established. Although there are some nanotechnology detection systems already in commercial use, there are still some significant shortfalls to overcome before a detection platform small enough to place on an occupational worker with the capability of detecting multiple hazards, simultaneously, in real-time, with precision and accuracy acceptable for compliance sampling can be realized. This ideal end-state is presently not a tangible reality, however, the nanotechnology reviewed could be augmented with existing detection technology and sampling methods to enhance the current detection methods and potentially reduce the laboratory analytical burden and detection time by making regulatory compliance sampling in the field a reality.

Notes

1. Headquarters Air Force Medical Support Agency, *Bioenvironmental Engineering Electronic Field Manual*, 2012.
2. Tiffany R. Heline, *Laboratory Sampling Guide*, AFRL-SA-WP-SR-2012-0008 (Wright-Patterson AFB, OH: United States Air Force School of Aerospace Medicine Occupational and Environmental Health Department, 2012).
3. National Institute of Occupational Safety and Health, "MF-34 NIOSH Manual of Analytical Methods," Centers for Disease Control and Prevention, 15 March 2013, <http://www.cdc.gov/niosh/docs/2003-154/>.
4. Air University, "AY15 AURIMS," Air Command Staff College Blackboard, 2015, https://acsc.blackboard.com/bbcswebdav/pid-2411925-dt-content-rid-5454399_4/xid-5454399_4, 13.
5. Nano.gov, "Benefits and Applications," National Nanotechnology Initiative, <http://www.nano.gov/you/nanotechnology-benefits>.
6. Aaron Rowe, "The 9 Best Nanotechnology-Powered Products," *Discover Magazine*, 29 June 2010, <http://discovermagazine.com/galleries/zen-photo/n/nanotech-products>.
7. Nanosphere, "Verigene System," Nanosphere Inc, <http://www.nanosphere.us/products/verigene-system>.
8. United States Environmental Protection Agency, "When and How was the EPA Created?," <http://publicaccess.supportportal.com/link/portal/23002/23012/Article/23723/When-and-how-was-the-EPA-created>.
9. United States Environmental Protection Agency, "Our Mission and What We Do," <http://www2.epa.gov/laws-regulations/our-mission-and-what-we-do>.
10. United States Environmental Protection Agency, "Laws and Executive Orders," <http://www2.epa.gov/laws-regulations/laws-and-executive-orders>.
11. Ibid.
12. Occupational Safety and Health Administration, "OSHA 3360 - Reflections on OSHA's History," U.S. Department of Labor, January 2009, https://www.osha.gov/history/OSHA_HISTORY_3360s.pdf.
13. United States Environmental Protection Agency, "Summary of the Occupational Safety and Health Act – 29 USC §651 et seq. (1970)," <http://www2.epa.gov/laws-regulations/summary-occupational-safety-and-health-act>.
14. Occupational Safety and Health Administration, "At-A-Glance: OSHA," U.S. Department of Labor. <https://www.osha.gov/Publications/3439at-a-glance.pdf>.
15. Occupational Safety and Health Administration, "OSHA Occupational Chemical Database," U.S. Department of Labor. <https://www.osha.gov/chemicaldata/#target>.
16. Department of Defense (DOD) Instruction 4715.6, *Environmental Compliance*, 24 April 1996.
17. Department of Defense (DOD) Instruction 6055.01, *DoD Safety and Occupational Health (SOH) Program*, 14 October 2014.
18. Department of Defense (DOD) Instruction 6055.05, *Occupational and Environmental Health (OEH)*, 11 November 2008.
19. Air Force Instruction (AFI) 90-801, *Environment, Safety, and Occupational Health Councils*, 29 December 2009.

-
20. Air Force Manual (AFMAN) 48-155, *Occupational and Environmental Health Exposure Controls*, 16 April 2010, 3.
 21. Ibid, 4.
 22. Ibid, 3.
 23. Ibid, 4.
 24. Ibid, 5.
 25. United States Environmental Protection Agency, "Drinking Water Contaminants," <http://water.epa.gov/drink/contaminants/index.cfm#List>.
 26. United States Environmental Protection Agency, "Unregulated Contaminant Monitoring Program," <http://water.epa.gov/lawsregs/rulesregs/sdwa/ucmr/index.cfm>.
 27. Tiffany R Heline, *Laboratory Sampling Guide*, AFRL-SA-WP-SR-2012-0008 (Wright-Patterson AFB, OH: United States Air Force School of Aerospace Medicine Occupational and Environmental Health Department, 2012), i-iii.
 28. Ibid, 13.
 29. Ibid, 60.
 30. Ibid, 85.
 31. Ibid, 120.
 32. Air Force Instruction (AFI) 48-145, *Occupational and Environmental Health Program*, 15 September 2011, 6.
 33. Defense Occupational and Environmental Health Readiness System (DOEHRS), "Process Hazards – AF List: 724367", Defense Information Systems Agency, <https://doehrsdw.csd.disa.mil/AnalyticalReporting/>.
 34. Ibid.
 35. Air Force Occupational Safety and Health Standard 48-20, *Occupational Noise and Hearing Conservation Program*, 10 May 2013, 33.
 36. Air Force Pamphlet 48-151, *Thermal Injury*, 18 November 2002, 9.
 37. Occupational Safety and Health Administration, "Ergonomics: The Study of Work – OSHA 3125 (Revised), United States Department of Labor, 2000, 5, <https://www.osha.gov/Publications/osha3125.pdf>.
 38. Occupational Safety and Health Administration. "OSHA Safety and Health Topics: Confined Spaces," United States Department of Labor, <https://www.osha.gov/SLTC/confinedspaces/>.
 39. Ibid.
 40. *Encyclopedia Britannica Online*, s.v. "Nanoparticle," <http://www.britannica.com/science/nanoparticle>.
 41. Nanogloss.com, "Gold Nanoparticles 101," Wordpress.org. <http://nanogloss.com/nanoparticles/gold-nanoparticles-101/#axzz3lzuifzNG>.
 42. Physics Central, "The Golden Age of Gold," American Physical Society, <http://www.physicscentral.com/explore/action/gold.cfm>.
 43. William Reusch, "Visible and Ultraviolet Spectroscopy," Michigan State University Department of Chemistry, <http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/UV-vis/spectrum.htm>.
 44. HACH®, "HACH DR 6000™ UV-VIS Spectrophotometer with RFID Technology – Parameter/Range/Reagent Information," HACH. <http://www.hach.com/dr-6000-uv-vis-spectrophotometer-with-rfid-technology/product-parameter-reagent?id=10239244800>.
 45. Ibid.

-
46. Ibid.
47. Xiaa Fan et al., *Colorimetric detection of DNA, small molecules, proteins, and ions using unmodified gold nanoparticles and conjugated polyelectrolytes*, Proceedings of the National Academy of Sciences of the United States of America (PNAS), 1, <http://www.pnas.org/content/107/24/10837.full.pdf>.
48. Ibid, 2.
49. Ibid, 2-3.
50. Tianhua Li et al., "A colorimetric nitrite detection system with excellent selectivity and high sensitivity based on Ag@ Au nanoparticles," *Analyst* 140, no. 4 (2015): 1076-1081, 1076.
51. Ibid, 1076.
52. P. Namour, M. Lepot, and N. Jarezcic, "Recent Trends in Monitoring of European Water Framework Directive Priority Substances Using Micro-Sensors: 2007-2009 Review," *Sensors*, 2010, no. 10: 7947-7978, <https://hal.archives-ouvertes.fr/hal-00536853>.
53. Ibid, 7952-7953, 7956-7958, 7960, 7963-7965.
54. Chao Wang and Chenxu Yu, "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review," *Reviews in Analytical Chemistry* 32, no. 1 (2013): 1-14, 3.
55. Ibid, 3.
56. Ibid, 5.
57. Ibid, 5.
58. Carmen E. Lisowski and James E. Hutchison, "Malonamide-functionalized gold nanoparticles for selective, colorimetric sensing of trivalent lanthanide ions," *Analytical chemistry* 81, no. 24 (2009): 10246-10253, 10246.
59. Ibid, 10247.
60. Ibid, 10247.
61. Thomas S. Zemanian and Yuehe Lin, *Nano-Engineered Electrochemical Sensors for Monitoring of Toxic Metals in Groundwater: Development of Novel Square Wave Anodic Stripping Voltammetry Electrodes Using Self Assembled Monolayers on Mesoporous Supports*, PNNL-16445 (Pacific Northwest National Lab Richland, WA, 2007), 3.
62. Ibid, 1.
63. Ibid, 16-17.
64. Yingchun Li et al., "Molecularly imprinted polymer decorated nanoporous gold for highly selective and sensitive electrochemical sensors," *Scientific reports*, no. 5 (2015), 1.
65. Ibid, 3.
66. Ibid, 3.
67. Ibid, 4.
68. Hadi AlQahtani et al., "Highly sensitive alkane odour sensors based on functionalised gold nanoparticles," *Sensors and Actuators B: Chemical* 160, no. 1 (2011): 399-404, 400.
69. Ibid, 400.
70. Ibid, 400.
71. Ibid, 400.
72. Niti Garg et al., "Robust Gold Nanoparticles Stabilized by Trithiol for Application in Chemiresistive Sensors," *Nanotechnology* 21, no. 40 (2010): 405-501, 405.
73. Ibid, 407.
74. Ibid, 407.
75. Ibid, 408.
76. Ibid, 409.

-
77. Ulrike Tisch and Hossam Haick, "Arrays of chemisensitive monolayer-capped metallic nanoparticles for diagnostic breath testing," *Reviews in Chemical Engineering* 26, no. 5-6 (2010): 171-179, 171.
78. Ibid, 171.
79. Ibid, 171.
80. Ibid, 171.
81. Ibid, 172.
82. Ibid, 172.
83. Hyun Jin In, Christopher R. Field, and Pehr E. Pehrsson, "Periodically porous top electrodes on vertical nanowire arrays for highly sensitive gas detection," *Nanotechnology* 22, no. 35 (2011): 355-501, 355.
84. Ibid, 358.
85. Ibid, 359.
86. Phys.org, "New Device Warns Workers of High Levels of Airborne Metals in Minutes Rather Than Weeks," *Phys.org*, 31 May 2012, <http://phys.org/news/2012-05-device-workers-highairborne-metals.html>.
87. Ibid.
88. Ibid.
89. Mark E. Fraser et al., "Real-time monitoring of airborne metals," *Photonics East (ISAM, VVDC, IEMB)*, International Society for Optics and Photonics, 1999, 262-270, 262.
90. Patrik Nilsson et al., "Laser Vaporizer-AMS for exposure assessment and detection of airborne engineered metal nanoparticles," *European Aerosol Conference 2012*, 2012.
91. Jorge L. Chávez et al., "Colorimetric detection with aptamer-gold nanoparticle conjugates: effect of aptamer length on response," *Journal of Nanoparticle Research* 14, no. 10 (2012): 1-11, 1.
92. Ibid, 3.
93. Andrew D. Hibbs and Geoffrey A. Barrall, *Engineered Bio-Molecular Nano-Devices/Systems* (Electronic Biosciences Inc, San Diego, CA, 2009), 92.
94. Ibid, 92.
95. Ibid, 93.
96. Rene Alvarez et al., *Rapid Identification of Bacterial Pathogens of Military Interest Using Surface-Enhanced Raman Spectroscopy*, NAMRU-SA-2014-58. (Naval Medical Research Unit San Antonio, Fort Sam Houston, TX, 2014), 8.
97. Ibid, 8.
98. Ibid, 9.
99. Ibid, 11.
100. Ferrari, Mauro, "Cancer nanotechnology: opportunities and challenges," *Nature Reviews Cancer* 5, no. 3 (2005): 161-171, 161.
101. Ibid, 165.
102. Ibid, 165.
103. Ibid, 165.
104. Ibid, 165.
105. Alexander Ohlinger et al., "Optically trapped gold nanoparticle enables listening at the microscale," *Physical review letters* 108, no. 1 (2012): 18-101, 18.
106. Ibid, 22.

-
107. R.C. Webb et al., "Thermal Transport Characteristics of Human Skin Measured in Vivo Using Ultrathin Conformal Arrays of Thermal Sensors and Actuators," *PLoS ONE*, 2015, no. 10, 118-131, 119.
108. Lance Wallace and John Toon, "Using Technology to Detect Gamma Radiation," Georgia Tech Research Institute, <http://www.gtri.gatech.edu/casestudy/using-nanotechnology-detect-gamma-radiation>.
109. Ibid.
110. Ibid.
111. Sniffing Out Cancer with Improved 'Electronic Nose' Sensors," Nanowerk News, 30 September 2015, <http://www.nanowerk.com/nanotechnology-news/newsid=41468.php>.
112. Nicole Kahn et al., "Dynamic Nanoparticle-Based Flexible Sensors: Diagnosis of Ovarian Carcinoma from Exhaled Breath," *Nano letters* (2015).
113. Ibid.
114. Mingo Pu, "Scientists Found a Natural Nanostructure to Control the Flow of Light," Nanotechnology Now, 4 October 2015, http://www.nanotech-now.com/news.cgi?story_id=52337.
115. Ibid.
116. Ibid.
117. Phys.org, "Better Bomb-Sniffing Technology with New Detector Material," *Phys.org*, November 4 2014, <http://phys.org/news/2014-11-bomb-sniffing-technology-detector-material.html>.
118. VAPORSENS, *Home Page*, <http://www.vaporsens.com/>.
119. VAPORSENS, *Product: VSENS Page*, <http://www.vaporsens.com/gas-vapor-sensors>.
120. VAPORSENS, *Technology: Sensors Page*, <http://www.vaporsens.com/sensors/>.
121. ScienceDaily, "Chip-Based Technology Enables Reliable Direct Detection of Ebola Virus," *ScienceDaily.com*, 25 September 2015, <http://www.sciencedaily.com/releases/2015/09/150925085341.htm>.
122. Ibid.
123. Ibid.
124. Government of Argentina, *Researchers Invent Device to Rapidly Detect Infectious Diseases*, 15 January 2014, Argentina Ministry of Science, Technology, and Productive Innovation <http://en.mincyt.gob.ar/casos-modelo/researchers-invent-device-to-rapidly-detect-infectious-diseases-9391>.
125. Ibid.
126. Ibid.
127. Ibid.
128. Yingchun Li et al., "Molecularly imprinted polymer decorated nanoporous gold for highly selective and sensitive electrochemical sensors," *Scientific reports* 5 (2015), 1.

Appendix A - Bioenvironmental Engineering Detection Capabilities

Detector Name	Class	Function	Capability	Medium	Technology
Hand Held Assay (HHA) ¹	Biological	Detection (Delayed)	Warfare Agents	Solid/Liquid	Chemo Luminescent
XMx ²	Biological	Collection	Aerosols	Air	Aerosol Capture/Liquid Impingement
BacT (Colilert®) ³	Biological	Detection (Delayed)	Coliform/Fecal Bacteria	Water	Colorimetric
Air Sampling Pump (Low/High Flow) ⁴	Chemical	Collection	Multiple	Air	Particulate/Vapor Collection
Dräger Chip Measurement System ⁵	Chemical	Detection (Delayed)	Multiple	Air	Colorimetric
Dräger Tubes ⁶	Chemical	Detection (Delayed)	Multiple	Air	Colorimetric
Hapsite Smart Plus / ER ⁷⁸	Chemical	Detection (Delayed)	VOCs	Air	GC/MS
4-Gas (Confined Space) Meter ⁹	Chemical	Detection (Real-Time)	VOCs/Gasses	Air	Photoionization
M256A1 ¹⁰	Chemical	Detection (Delayed)	Warfare Agents	Air	Colorimetric
Indoor Air Quality Meter ¹¹	Chemical	Detection (Real-Time)	Atmospheric	Environmental	NDIR, Thermistor, Thin-Film Capacitive, Electro-chemical
HazMat ID / Elite ¹²	Chemical	Detection (Delayed)	Covalent Bonds	Solids/Liquids	FTIR
Ahura FD / FirstDefender™ RM ¹³	Chemical	Detection (Delayed)	VOCs	Solids/Liquids	Raman
Hach Meter ¹⁴	Chemical	Detection (Delayed)	Multiple	Water	Colorimetric
M272 ¹⁵	Chemical	Detection (Delayed)	Warfare Agents	Water	Colorimetric
Hapsite (Headspace Analyzer) ¹⁶	Chemical	Detection (Delayed)	VOCs	Water/Soil	GC/MS
Wet Bulb Global Thermometer ¹⁷	Physical	Detection (Real-Time)	Atmospheric	Environmental	Thermistor
Noise Dosimeter ¹⁸	Physical	Detection (Delayed)	Noise Dosimetry	Noise	SPL
Noise Sound Level Meter (SLM) ¹⁹	Physical	Detection (Real-Time)	Noise Source	Noise	Microphone - RMS
Radeco ²⁰	Radiological	Collection	Air	Ionizing	Air Filter
ADM-300 (Alpha Probe) ²¹	Radiological	Detection (Real-Time)	Alpha	Ionizing	Scintillation
451P ²²	Radiological	Detection (Real-Time)	Gamma	Ionizing	Ion Chamber
SAM 935/940 ²³	Radiological	Detection (Real-Time)	Gamma/Beta	Ionizing	Crystal Scintillation
ADM-300 (Beta Probe) ²⁴	Radiological	Detection (Real-Time)	Gamma/Beta	Ionizing	Geiger Mueller
ADM-300 (Gamma Probe) ²⁵	Radiological	Detection (Real-Time)	Gamma/Beta	Ionizing	Geiger Mueller
EPD ²⁶	Radiological	Detection (Real-Time)	Gamma/Beta	Ionizing	Multi Detector
ADM-300 (X-Ray Probe) ²⁷	Radiological	Detection (Real-Time)	Gamma/X-Ray	Ionizing	Scintillation
Narda Probe ²⁸	Radiological	Detection (Real-Time)	EMF	Non-Ionizing	Diode

Notes

1. United States Navy, "Information Paper: Hand Held Assay (HHA)," Navy Environmental and Preventive Medicine Unit TWO. [http://www.med.navy.mil/sites/nepmu2/Documents/lab/Hand%20Held%20Assays%20\(HHA\).pdf](http://www.med.navy.mil/sites/nepmu2/Documents/lab/Hand%20Held%20Assays%20(HHA).pdf).
2. Dycor, "XMX/2L-MIL Bioaerosol Sampler – Military," Collecting Airborne Particles, <http://www.dycor.com/what-do-we-do/aerosol-analysis/air-samplers/xmx2l-mil/>.
3. IDEXX, "Colilert®," Water Testing Solutions-Products and Services, <https://www.idexx.com/water/products/colilert.html>.
4. SKC, "Air Sampling Pumps to 5 L/min," Sampling Pumps, http://www.skinc.com/catalog/index.php?cPath=100000000_101000000.
5. Dräger, "Dräger Chip-Measurement System," Chemical Industry, http://www.draeger.com/sites/enus_us/Pages/Chemical-Industry/Draeger-Chip-Measurement-System.aspx.
6. Dräger, *Dräger-Tubes and CMS-Handbook Soil, Water, and Air Investigations as well as Technical Gas Analysis, 16th Edition*, 2011, <http://www.draeger.com/sites/assets/PublishingImages/Products/tubes-for-short-term-measurements/US/tube-cms-handbook-9092086-us.pdf>.
7. INFICON, "HAPSITE ER Chemical Identification System," Overview, <http://products.inficon.com/en-us/Product/Detail/HAPSITE-ER-Identification-System?path=Products%2Fpg-ChemicalDetection>.
8. INFICON, "HAPSITE Smart Plus Chemical Identification System," Overview, <http://products.inficon.com/en-us/Product/Detail/HAPSITE-Smart-Plus-Chemical-Identification-System?path=Products%2Fpg-ChemicalDetection>.
9. MSA – The Safety Company, "The Sirius® Multigas Detector," Data Sheet: Sirius Multigas Detector, <http://s7d9.scene7.com/is/content/minesafetyappliances/Sirius%20Bulletin%20-%20EN>.
10. Department of Defense (DOD), "Information Paper: M256 Series Chemical Agent Detector Kit," GulfLINK: Office of the Special Assistant to Gulf War Illnesses, <http://www.gulflink.osd.mil/m256/>.
11. TSI, "IAQ-CALC Indoor Air Quality Meter 7545," Products, <http://www.tsi.com/iaq-calc-indoor-air-quality-meters-7545/>.
12. Smiths Detection, "HazmatID Elite: Handheld FT-IR Chemical Identifier," Products and Solutions: Chemical Identification, <http://www.smithsdetection.com/en/products-solutions/chemical-identification/57-chemical-identification/hazmatid-elite.html#.ViRDwfmrSUK>.
13. Thermo Scientific, "FirstDefender™ RM Chemical Identification System," Products, <http://www.thermoscientific.com/en/product/firstdefender-rm-chemical-identification-system.html>.
14. HACH®, "DR 3900 Benchtop Spectrophotometer," Lab Instruments: Spectrophotometers, <http://www.hach.com/spectrophotometers/dr-3900-benchtop-spectrophotometer/family?productCategoryId=35547203834>.
15. United States Army Technical Manual (TM) 3-6665-319-10, *Water Testing Kit, Chemical Agents: M272 (NSN 6665-01-134-0885)*, 30 November 1983.

-
16. INFICON, "Headspace Sampling System," Products, <http://products.inficon.com/en-us/Product/Detail/Headspace-Sampling-System?path=Products%2Fpg-ChemicalDetection>.
 17. 3M, "3M™ QuestTemp° Heat Stress Monitor QT-44," Heat Stress Monitors, http://solutions.3m.com/wps/portal/3M/en_EU/PPE_SafetySolutions_EU/Safety/Product_Catalogue/~PPE-Safety-Solutions/Detection-Solutions/Heat-Stress-Monitors?N=5023587+3294857473&rt=r3.
 18. 3M, "NoisePro™ User Manual," 3M Personal Safety Division, <http://multimedia.3m.com/mws/media/778904O/noisepro-noise-dosimeter-user-manual.pdf>.
 19. Quest® Technologies, "Basic Sound Level Meters," Raeco Rents Products Page, <http://www.raecorents.com/products/noise/3M-Quest-2200-SLM/3M-basic-sound-level-meter-bro.pdf>.
 20. RADēCO, "US Air Force and National Guard Air Sampling Kit," Products, <http://www.radecoinc.com/products/usaf-kit>.
 21. Dennis R. Armstrong et al., *Evaluation of Nuclear Research Corporation's ADM-300 Radiation Detection, Indication, and Computation (RADIAC) Instrument*, AL-TR-1992-0010 (Armstrong Lab, Brooks AFB TX, 1992).
 22. Fluke Biomedical, "451P Pressurized μR Ion Chamber Radiation Survey Meter," Products, <http://www.flukebiomedical.com/biomedical/usen/radiation-safety/survey-meters/451p-pressurized-ion-chamber-radiation-detector-survey-meter.htm?pid=54793>.
 23. BNC – Berkley Nucleonics Corporation, "SAM 940 Defender/Revealer Isotope Identification with Reachback Program," Overview, http://www.berkeleynucleonics.com/products/model_940.html.
 24. Dennis R. Armstrong et al., *Evaluation of Nuclear Research Corporation's ADM-300 Radiation Detection, Indication, and Computation (RADIAC) Instrument*, AL-TR-1992-0010 (Armstrong Lab, Brooks AFB TX, 1992).
 25. Ibid.
 26. Fisher Scientific, "Thermo Scientific™ EPD Electronic Personal Dosimeters," Description and Specifications, <https://www.fishersci.com/shop/products/thermo-scientific-epd-mk2-electronic-personal-dosimeter-with-coin-battery-cap/19166365>.
 27. Dennis R. Armstrong et al., *Evaluation of Nuclear Research Corporation's ADM-300 Radiation Detection, Indication, and Computation (RADIAC) Instrument*, AL-TR-1992-0010 (Armstrong Lab, Brooks AFB TX, 1992).
 28. Narda Safety Test Solutions, "High Frequency Broad Band Meters," Products, http://www.narda-sts.us/products_highfreq_bband.php.

Appendix B - The 50 Most Prevalent Hazards across Air Force Installations¹

Hazard Name	Hazard Count	Percent of All Hazards	Prevalance by Location	Prevalence by Process
Noise	25339	14.9%	97.3%	97.3%
Thermal Stress	12073	7.1%	70.2%	94.6%
Petroleum Distillates	10544	6.2%	74.5%	68.9%
Ergonomic Hazards	9340	5.5%	58.5%	86.5%
Kinetic Hazards	7787	4.6%	56.4%	79.7%
Toluene	5128	3.0%	92.0%	78.4%
Chromium Compounds	4899	2.9%	87.2%	64.9%
Isopropanol	4446	2.6%	88.8%	75.7%
Acetone	3789	2.2%	84.6%	79.7%
Methyl Ethyl Ketone	3629	2.1%	86.2%	73.0%
Lead Compounds	3512	2.1%	88.3%	71.6%
Jet Fuels	3411	2.0%	71.3%	58.1%
Xylene	3277	1.9%	87.8%	75.7%
Bloodborne Pathogens	2969	1.7%	71.8%	71.6%
Silica/Silicate Compounds	2420	1.4%	53.7%	67.6%
Methanol	2239	1.3%	71.8%	78.4%
Laser Hazards	2219	1.3%	56.9%	58.1%
Benzene	1884	1.1%	80.9%	60.8%
Ethanol	1869	1.1%	66.0%	77.0%
Ionizing Radiation	1772	1.0%	85.6%	59.5%
Confined Space	1714	1.0%	77.7%	64.9%
RFR	1662	1.0%	78.7%	59.5%
Cadmium Compounds	1563	0.92%	74.5%	56.8%
Ultraviolet Radiation	1511	0.89%	80.9%	60.8%
Formaldehyde	1387	0.82%	65.4%	64.9%
Ethylene Glycol	1331	0.78%	74.5%	74.3%
Inorganic Acids	1134	0.67%	63.8%	64.9%
Particulates (Not Specified)	994	0.58%	63.3%	78.4%
Aluminum Compounds	943	0.55%	60.6%	51.4%
Ethyl Benzene	939	0.55%	65.4%	55.4%
Zinc	901	0.53%	53.7%	45.9%
Titanium	863	0.51%	51.6%	55.4%
N-Hexane	833	0.49%	56.9%	67.6%
N-Butyl Acetate	821	0.48%	59.0%	54.1%
Copper	817	0.48%	66.5%	58.1%
Propane	726	0.43%	50.0%	64.9%
Manganese	724	0.43%	54.3%	31.1%
Methyl Isobutyl Ketone	668	0.39%	59.0%	48.6%
Mineral Oil	652	0.38%	58.5%	59.5%
Cyclohexanone	647	0.38%	49.5%	48.6%
Carbon Monoxide	645	0.38%	75.0%	45.9%
Iron	618	0.36%	47.3%	31.1%
Tin	612	0.36%	53.2%	44.6%
2-Butoxyethanol	593	0.35%	54.8%	55.4%
Methylene Chloride	572	0.34%	65.4%	56.8%
Nickel Compounds	566	0.33%	52.7%	44.6%
Asbestos	533	0.31%	50.0%	59.5%
Nitrogen	515	0.30%	48.4%	39.2%
Heptane	509	0.30%	50.0%	52.7%
Molybdenum	508	0.30%	41.0%	31.1%

LEGEND

Biological
Chemical - Inorganic
Chemical - Organic
Physical
Radiation

Notes

-
1. Defense Occupational and Environmental Health Readiness System (DOEHRS), “Process Hazards – AF List: 724367,” Defense Information Systems Agency, <https://doehrsdw.csd.disa.mil/AnalyticalReporting/>.



Appendix C - Results of Research Reviewed Compared to Evaluation Criteria

Research Reviewed	Evaluation Criteria	Sensitivity	Selectivity	Inst Det	Simult Det	Portable	Reusable	Varied Env	Det in	Det in Air	Organic	Gas	Metal	Biological	Radiological	Physical
Type of Nanotech	Sub-Type															
Electrochemical	Film - 2D AuNP Array ¹	X	X	X	X	X	X			X	X					
Electrochemical	Film - Au/PtNP/Graphene ²	X	X	X				X		X	X					
Electrochemical	Film - AuNP ³	X	X	X		X	X				X					
Electrochemical	Film - AuNP ⁴	X	X	X		X					X					
Electrochemical	Film - AuNP Interdig Capacitive ⁵	X	X	X	X									X		
Electrochemical	Film - AuNP Ligands ⁶	X	X					X		X	X					
Electrochemical	Film - AuNP Ligands ⁷					X	X	X		X	X					
Electrochemical	Film - AuNP SW Stripping ⁸	X	X	X	X			X	X				X			
Electrochemical	Film - CuNP Monolayer-Capped ⁹	X					X	X		X	X					
Electrochemical	Film - Dodecane Core/Shell ¹⁰						X	X			X					
Electrochemical	Film - MIP-NPGL ¹¹	X	X	X	X	X	X		X	X	X	X	X	X		
Electrochemical	Film - MCNPs ¹²	X	X	X			X			X				X		
Electrochemical	Film - SAMMS-SWASV ¹³	X	X	X	X								X			
Electrochemical	Film - Trithiol Capped ¹⁴	X									X					
Electrochemical	Film - Tyrosine/AuNP/T-NH2 ¹⁵	X	X	X				X	X		X					
Electrochemical	Film - Vapor Droplet Interaction ¹⁶	X	X					X		X	X					
Electrochemical	Film - Vapor IDA Self-Assem	X						X								
Electrochemical	Nanorod - AuNP Fiber Optic ¹⁸	X	X				X		X			X				
Electrochemical	Nanotube - Single Walled Carbon ¹⁹	X	X								X	X				
Electrochemical	Nanowire - Silicon ²⁰	X	X	X		X	X	X		X	X	X		X		
Electrochemical	Nanowire - Silicon ²¹	X	X	X			X									
Electrochemical	Nanowire - Silicon (B-Doped) ²²	X	X	X			X		X				X	X		
Electrochemical	Nanowire - Silicon V Array Porous ²³	X	X	X	X	X	X				X					
Electrochemical	Nanowire - ZnO on ITO SiO/C ²⁴	X								X	X					
Electrochemical	Thermal Actuator Si/Cr/Au Wafer ²⁵	X	X	X		X	X									X
Electrochemical	Film - AuNPs Lateral Flow Strip ²⁶								X		X					
Electrochemical	Film - Cat-Spec Funct ²⁷								X		X					
Optical	Colorimetric ²⁸								X				X			
Optical	Colorimetric - Agg Direct Sen ²⁹							X	X		X					
Optical	Colorimetric - Immunoassay Strip ³⁰								X					X		
Optical	Colorimetric - Ligand Based ³¹	X	X	X					X		X		X			
Optical	Colorimetric - Ligand Based ³²	X	X	X				X	X		X					
Optical	Colorimetric - Ligand Based ³³	X	X	X					X				X			
Optical	Colorimetric - Ligand Based ³⁴	X	X	X		X			X					X		
Optical	Colorimetric - Lig Cysteine AuNP ³⁵								X					X		
Optical	Colorimetric - Non-crosslinking ³⁶								X		X					
Optical	Colorimetric - AuNP Conj Polymer ³⁷	X		X		X			X		X		X	X		
Optical	Colorimetric Aptamer AuNP Conj ³⁸	X	X	X					X					X		
Optical	Colorimetric - Crosslinking ³⁹								X		X					
Optical	Optical Sensor ⁴⁰								X			X				
Optical	Optical Sensor - SS DNA ⁴¹	X	X						X				X			
Optical	Optical Tweezers - Pos Track	X	X						X							
Optical	SERS - AgNP ⁴³	X	X	X	X	X			X					X		
Optical	SERS - AgNP - MIP ⁴⁴	X	X	X							X					
Optical	SERS - AuNP substrate ⁴⁵	X	X						X		X					
Optical	SERS - Ga2O3/Ag Nanowire ⁴⁶	X							X		X					
Optical	SERS - Optical SiO2 -AuNP ⁴⁷	X	X	X								X				
Optical	SPR - Capped AuNPs ⁴⁸	X	X			X										

Notes

1. C. Hanisch et al., "Polymer-Metal Nanocomposites with 2-Dimensional Au Nanoparticle Arrays for Sensoric Applications," *Journal of Physics: Conference Series*, 2008, vol. 100, part 5.
2. Madhav Gautam and A. H. Jayatissa, "Detection of Organic Vapors by Graphene Films Functionalized with Metallic Nanoparticles," *Journal of Applied Physics*, 112, 11 (2012): 114-326.
3. David B. Pedersen and E. J. Duncan, *Surface Plasmon Resonance Spectroscopy of Gold Nanoparticle-Coated Substrates: Use as an Indicator of Exposure to Chemical Warfare Simulants*, DRDC-SUFFIELD-TR-2005-109, (Defence Research and Development Suffield Alberta, 2005).
4. D.S. Pedersen and S. Wang, *Current flow through two dimensional arrays of metal nanoparticles as a novel sensor platform*, DRDC-SUFFIELD-TM-2009-068 (Defence Research and Development Suffield, Alberta, 2009).
5. Zeynep Altintas et al., "Gold nanoparticle modified capacitive sensor platform for multiple marker detection," *Talanta*, 118 (2014): 270-276.
6. R.R. Smardzewski et al., *Nanoelectronic chemical sensors: theory and experiment* (Geo-Centers Inc., Aberdeen Proving Ground, MD, 2004).
7. Ibid.
8. Jinfen Wang et al., "Simultaneous detection of copper, lead and zinc on tin film/gold nanoparticles/gold microelectrode by square wave stripping voltammetry," *Electroanalysis* 24, no. 8 (2012): 1783-1790.
9. Chuan-Jian Zhong et al., *Synthesis and Thin Film Assembly of Copper Nanoparticles for Sensing Contaminants in Aircraft Cabins*, State University of New York at Binghamton Research Foundation, 2008.
10. Hadi AlQahtani et al., "Highly sensitive alkane odour sensors based on functionalised gold nanoparticles," *Sensors and Actuators B: Chemical* 160, no. 1 (2011): 399-404.
11. Yingchun Li et al., "Molecularly imprinted polymer decorated nanoporous gold for highly selective and sensitive electrochemical sensors," *Scientific reports* 5 (2015).
12. Ulrike Tisch and Hossam Haick, "Arrays of chemisensitive monolayer-capped metallic nanoparticles for diagnostic breath testing," *Reviews in Chemical Engineering* 26, no. 5-6 (2010): 171-179.
13. Thomas S. Zemanian and Yuehe Lin, *Nano-Engineered Electrochemical Sensors for Monitoring of Toxic Metals in Groundwater: Development of Novel Square Wave Anodic Stripping Voltammetry Electrodes Using Self Assembled Monolayers on Mesoporous Supports*, PNNL-16445 (Pacific Northwest National Lab Richland, WA, 2007).
14. Niti Garg et al., "Robust Gold Nanoparticles Stabilized by Trithiol for Application in Chemiresistive Sensors," *Nanotechnology* 21, no. 40 (2010): 405-501 6.
15. Na Wang et al., "Gold nanoparticles-enhanced bisphenol A electrochemical biosensor based on tyrosinase immobilized onto self-assembled monolayers-modified gold electrode," *Chinese Chemical Letters* 25, no. 5 (2014): 720-722.
16. Kun Luo et al., "Thin Film Assembly of Gold Nanoparticles for Vapor Sensing via Droplet Interfacial Reaction," *Journal of Materials Science & Technology* 29, no. 5 (2013): 401-405.
17. Ibid.

-
18. Jeffrey Scott Crosby, "Mercury Detection with Gold Nanoparticles: Investigating Fundamental Phenomena and Expanding Applications," PhD diss., University of California, Berkeley, 2013.
 19. Jing Li and Yijiang Lu, "Nanostructure-engineered chemical sensors for hazardous gas and vapor detection," International Society for Optics and Photonics, *Optics East*, 2004, 222-231.
 20. C. Hanisch et al., "Periodically Porous Top Electrodes on Vertical Nanowire Arrays for Highly Sensitive Gas Detection," *Nanotechnology*, 2011, no. 22, 355-501.
 21. "NRL SiN-VAPOR Technology," Naval-Technology, 19 August 2013, <http://www.naval-technology.com/news/newsnrl-develops-sinvapor-technology>.
 22. Yi Cui et al., "Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species," *Science* 293, no. 5533 (2001): 1289-1292.
 23. "NRL SiN-VAPOR Technology," Naval-Technology, 19 August 2013, <http://www.naval-technology.com/news/newsnrl-develops-sinvapor-technology>.
 24. Gregory J. Ehlert et al., *Hierarchical Carbon Fibers with ZnO Nanowires for Volatile Sensing in Composite Curing (Postprint)*, (Air Force Research Lab, Wright-Patterson AFB, OH, Structural Materials Division, 2014).
 25. R. C. Webb et al., "Thermal Transport Characteristics of Human Skin Measured in Vivo Using Ultrathin Conformal Arrays of Thermal Sensors and Actuators," *PLoS ONE*, 2015, no. 10, 118-131.
 26. Chao Wang and Chenxu Yu, "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review," *Reviews in Analytical Chemistry* 32, no. 1 (2013): 1-14.
 27. Ibid.
 28. Ibid.
 29. Ibid.
 30. Ibid.
 31. Tianhua Li et al., "A colorimetric nitrite detection system with excellent selectivity and high sensitivity based on Ag@ Au nanoparticles," *Analyst* 140, no. 4 (2015): 1076-1081.
 32. Kelong Ai, Yanlan Liu, and Lehui Lu, "Hydrogen-bonding recognition-induced color change of gold nanoparticles for visual detection of melamine in raw milk and infant formula," *Journal of the American Chemical Society* 131, no. 27 (2009): 9496-9497.
 33. Carmen E. Lisowski and James E. Hutchison, "Malonamide-functionalized gold nanoparticles for selective, colorimetric sensing of trivalent lanthanide ions," *Analytical chemistry* 81, no. 24 (2009): 10246-10253.
 34. Yong-Qiang Dang et al., "Selective detection of trace Cr³⁺ in aqueous solution by using 5, 5'-dithiobis (2-nitrobenzoic acid)-modified gold nanoparticles," *ACS applied materials & interfaces* 1, no. 7 (2009): 1533-1538.
 35. Chao Wang and Chenxu Yu, "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review," *Reviews in Analytical Chemistry* 32, no. 1 (2013): 1-14.
 36. Ibid.
 37. Xiaa Fan et al., *Colorimetric detection of DNA, small molecules, proteins, and ions using unmodified gold nanoparticles and conjugated polyelectrolytes*, Proceedings of the National Academy of Sciences of the United States of America (PNAS), <http://www.pnas.org/content/107/24/10837.full.pdf>.
 38. Jorge L. Chávez et al., "Colorimetric detection with aptamer-gold nanoparticle conjugates: effect of aptamer length on response," *Journal of Nanoparticle Research* 14, no. 10 (2012): 1-11.

-
39. Chao Wang and Chenxu Yu, "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review," *Reviews in Analytical Chemistry* 32, no. 1 (2013): 1-14.
40. Ibid.
41. Chia-Chen Chang et al., "An amplified surface plasmon resonance 'turn-on' sensor for mercury ion using gold nanoparticles," *Biosensors and Bioelectronics* 30, no. 1 (2011): 235-240.
42. Alexander Ohlinger et al., "Optically trapped gold nanoparticle enables listening at the microscale," *Physical review letters* 108, no. 1 (2012): 18-101.
43. Rene Alvarez et al., *Rapid Identification of Bacterial Pathogens of Military Interest Using Surface-Enhanced Raman Spectroscopy*, NAMRU-SA-2014-58 (Naval Medical Research Unit San Antonio, Fort Sam Houston, TX, 2014).
44. Ellen Holthoff and Dimitra Stratis-Cullum, *A nanosensor for explosives detection based on molecularly imprinted polymers (MIPs) and Surface-enhanced Raman Scattering (SERS)*, ARL-TR-5092 (Army Research Lab, Adelphi, MD, Sensors and Electron Devices Directorate, 2010).
45. Nahla A. Hatab et al., "Detection and analysis of cyclotrimethylenetrinitramine (RDX) in environmental samples by surface-enhanced Raman spectroscopy," *Journal of Raman Spectroscopy* 41, no. 10 (2010): 1131-1136.
46. S. M. Prokes, O. J. Glembocki, and R. W. Rendell, *Highly Efficient Surface Enhanced Raman Scattering (SERS) Nanowire/Ag Composites* (Naval Research Lab, Washington, DC, Electronics Science and Technology Division, 2007).
47. D. Buso et al., "Selective optical detection of H₂ and CO with SiO₂ sol-gel films containing NiO and Au nanoparticles," *Nanotechnology* 18, no. 47 (2007): 475-505.
48. Sandhya Banti Dutta Borah et al., "Heavy Metal Ion Sensing By Surface Plasmon Resonance on Gold Nanoparticles," *ADBU Journal of Engineering Technology* 1 (2014).

Bibliography

- 3M. "3M™ QuestTemp° Heat Stress Monitor QT-44." Heat Stress Monitors.
http://solutions.3m.com/wps/portal/3M/en_EU/PPE_SafetySolutions_EU/Safety/Product_Catalogue/~/PPE-Safety-Solutions/Detection-Solutions/Heat-Stress-Monitors?N=5023587+3294857473&rt=r3 (accessed 11 October 2015).
- 3M "NoisePro™ User Manual" 3M Personal Safety Division.
<http://multimedia.3m.com/mws/media/7789040/noisepro-noise-dosimeter-user-manual.pdf>. (accessed 11 October 2015).
- Ai, Kelong, Yanlan Liu, and Lehui Lu. "Hydrogen-bonding recognition-induced color change of gold nanoparticles for visual detection of melamine in raw milk and infant formula." *Journal of the American Chemical Society* 131, no. 27 (2009): 9496-9497.
- Air Force Instruction (AFI) 90-801. *Environment, Safety, and Occupational Health Councils*, 29 December 2009.
- Air Force Instruction (AFI) 48-145. *Occupational and Environmental Health Program*, 15 September 2011.
- Air Force Manual (AFMAN) 48-155. *Occupational and Environmental Health Exposure Controls*, 16 April 2010.
- Air Force Occupational Safety and Health Standard 48-20. *Occupational Noise and Hearing Conservation Program*, 10 May 2013.
- Air Force Pamphlet 48-151, *Thermal Injury*, 18 November 2002.
- Air University. "AY15 AURIMS." Air Command Staff College Blackboard. 2015.
https://acsc.blackboard.com/bbcswebdav/pid-2411925-dt-content-rid-5454399_4/xid-5454399_4 (accessed 2 September 2015).
- AlQahtani, Hadi, Mark Sugden, Delia Puzzovio, Lee Hague, Nic Mullin, Tim Richardson, and Martin Grell. "Highly sensitive alkane odour sensors based on functionalised gold nanoparticles." *Sensors and Actuators B: Chemical* 160, no. 1 (2011): 399-404.
- Altintas, Zeynep, Sreenivasa Saravan Kallemudi, and Yasar Gurbuz. "Gold nanoparticle modified capacitive sensor platform for multiple marker detection." *Talanta* 118 (2014): 270-276.
- Alvarez, Rene, Alexander J. Burdette, Xiaomeng Wu, Christian Kotanen, Yiping Zhao, and Ralph A. Tripp. *Rapid Identification of Bacterial Pathogens of Military Interest Using Surface-Enhanced Raman Spectroscopy*. No. NAMRU-SA-2014-58. Naval Medical Research Unit (San Antonio), Fort Sam Houston, TX, 2014.

- Armstrong, Dennis R., William V. Hoak, Jocelyn Nixon, and David G. Martin. *Evaluation of Nuclear Research Corporation's ADM-300 Radiation Detection, Indication, and Computation (RADIAC) Instrument*. No. AL-TR-1992-0010. Armstrong Lab, Brooks AFB TX, 1992.
- BNC – Berkley Nucleonics Corporation. “SAM 940 Defender / Revealer Isotope Identification with Reachback Program.” Overview.
http://www.berkeleynucleonics.com/products/model_940.html. (accessed 11 October 2015).
- Borah, Sandhya Banti Dutta, Sunandan Baruah, Waleed S. Mohammed, and Joydeep Dutta. "Heavy Metal Ion Sensing By Surface Plasmon Resonance on Gold Nanoparticles." *ADBU Journal of Engineering Technology* 1 (2014).
- Buso, D., G. Busato, M. Guglielmi, A. Martucci, V. Bello, G. Mattei, P. Mazzoldi, and M. L. Post. "Selective optical detection of H₂ and CO with SiO₂ sol–gel films containing NiO and Au nanoparticles." *Nanotechnology* 18, no. 47 (2007): 475505.
- Chang, Chia-Chen, Shenhsiung Lin, Shih-Chung Wei, Chen-Yu Chen, and Chii-Wann Lin. "An amplified surface plasmon resonance “turn-on” sensor for mercury ion using gold nanoparticles." *Biosensors and Bioelectronics* 30, no. 1 (2011): 235-240.
- Chávez, Jorge L., Robert I. MacCuspie, Morley O. Stone, and Nancy Kelley-Loughnane. "Colorimetric detection with aptamer–gold nanoparticle conjugates: effect of aptamer length on response." *Journal of Nanoparticle Research* 14, no. 10 (2012): 1-11.
- Crosby, Jeffrey Scott. "Mercury Detection with Gold Nanoparticles: Investigating Fundamental Phenomena and Expanding Applications." PhD diss., University of California, Berkeley, 2013.
- Cui, Yi, Qingqiao Wei, Hongkun Park, and Charles M. Lieber. "Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species." *Science* 293, no. 5533 (2001): 1289-1292.
- Dang, Yong-Qiang, Hong-Wei Li, Bin Wang, Lei Li, and Yuqing Wu. "Selective detection of trace Cr³⁺ in aqueous solution by using 5, 5'-dithiobis (2-nitrobenzoic acid)-modified gold nanoparticles." *ACS applied materials & interfaces* 1, no. 7 (2009): 1533-1538.
- Defense Occupational and Environmental Health Readiness System (DOEHRS). “Process Hazards – AF List: 724367”. Defense Information Systems Agency.
<https://doehrsdw.csd.disa.mil/AnalyticalReporting/>. (accessed 31 July 2015).
- Department of Defense (DOD). “Information Paper: M256 Series Chemical Agent Detector Kit”. GulfLINK: Office of the Special Assistant to Gulf War Illnesses.
<http://www.gulflink.osd.mil/m256/>. (accessed 11 October 2015).

Department of Defense (DOD) Instruction 4715.6. *Environmental Compliance*, April 24, 1996.

Department of Defense (DOD) Instruction 6055.01. *DoD Safety and Occupational Health (SOH) Program*, October 14, 2014.

Department of Defense (DOD) Instruction 6055.05. *Occupational and Environmental Health (OEH)*, November 11, 2008.

Dräger. “Dräger Chip-Measurement System.” Chemical Industry.
http://www.draeger.com/sites/enus_us/Pages/Chemical-Industry/Draeger-Chip-Measurement-System.aspx. (accessed 11 October 2015).

———. *Dräger-Tubes and CMS-Handbook Soil, Water, and Air Investigations as well as Technical Gas Analysis, 16th Edition*, 2011.
<http://www.draeger.com/sites/assets/PublishingImages/Products/tubes-for-short-term-measurements/US/tube-cms-handbook-9092086-us.pdf>. (accessed 11 October 2015).

Dycor. “XMX/2L-MIL Bioaerosol Sampler – Military.” Collecting Airborne Particles.
<http://www.dycor.com/what-do-we-do/aerosol-analysis/air-samplers/xmx2l-mil/>. (accessed 11 October 2015).

Ehlert, Gregory J., D. Savastano, Z. Bai, and G. P. Tandon. *Hierarchical Carbon Fibers with ZnO Nanowires for Volatile Sensing in Composite Curing (Postprint)*. Air Force Research Lab, Wright-Patterson AFB, OH, Structural Materials Division, 2014.

Encyclopedia Britannica Online, s.v. “Nanoparticle,” <http://www.britannica.com/science/nanoparticle> (accessed 10 October 2015). (King, Stephen).

Fan, Xiaa, Xiaolei Zuob, Renqiang Yangc, Yi Xiaob, Di Kangb, Alexis Vallée-Bélisleb, Xiong Gongga, Jonathan D. Yuena, Ben B. Y. Hsua, Alan J. Heegera, and Kevin W. Plaxcob. *Colorimetric detection of DNA, small molecules, proteins, and ions using unmodified gold nanoparticles and conjugated polyelectrolytes*. Proceedings of the National Academy of Sciences of the United States of America (PNAS)
<http://www.pnas.org/content/107/24/10837.full.pdf> (accessed 22 September 2015).

Ferrari, Mauro. "Cancer nanotechnology: opportunities and challenges." *Nature Reviews Cancer* 5, no. 3 (2005): 161-171.

Fisher Scientific. “Thermo Scientific™ EPD Electronic Personal Dosimeters” Description and Specifications. <https://www.fishersci.com/shop/products/thermo-scientific-epd-mk2-electronic-personal-dosimeter-with-coin-battery-cap/19166365>. (accessed 11 October 2015).

- Fluke Biomedical. "451P Pressurized μ R Ion Chamber Radiation Survey Meter." Products. <http://www.flukebiomedical.com/biomedical/usen/radiation-safety/survey-meters/451p-pressurized-ion-chamber-radiation-detector-survey-meter.htm?pid=54793>. (accessed 11 October 2015).
- Fraser, Mark E., Amy J. Hunter, and Steven J. Davis. "Real-time monitoring of airborne metals." In *Photonics East (ISAM, VVDC, IEMB)*, 262-270. International Society for Optics and Photonics, 1999.
- Garg, Niti, Ashok Mohanty, Nathan Lazarus, Lawrence Schultz, Tony R. Rozzi, Suresh Santhanam, Lee Weiss, Jay L. Snyder, Gary K. Fedder, and Rongchao Jin. "Robust Gold Nanoparticles Stabilized by Trithiol for Application in Chemiresistive Sensors." *Nanotechnology*, 21, 40 (2010): 405-501
- Gautam, Madhav and AH Jayatissa. "Detection of Organic Vapors by Graphene Films Functionalized with Metallic Nanoparticles." *Journal of Applied Physics*, 112, 11 (2012): 114-326.
- Government of Argentina, *Researchers Invent Device to Rapidly Detect Infectious Diseases*, January 15, 2014. Argentina Ministry of Science, Technology, and Productive Innovation <http://en.mincyt.gob.ar/casos-modelo/researchers-invent-device-to-rapidly-detect-infectious-diseases-9391>. (accessed 9 October 2015).
- HACH®. "HACH DR 6000™ UV-VIS Spectrophotometer with RFID Technology – Parameter/Range/Reagent Information." HACH. <http://www.hach.com/dr-6000-uv-vis-spectrophotometer-with-rfid-technology/product-parameter-reagent?id=10239244800> (accessed 22 September 2015).
- . "DR 3900 Benchtop Spectrophotometer" Lab Instruments: Spectrophotometers. <http://www.hach.com/spectrophotometers/dr-3900-benchtop-spectrophotometer/family?productCategoryId=35547203834> (accessed 11 October 2015).
- Hanisch, C. A. Kulkarni, V. Zaporotjchenko, and F. Faupel. "Polymer-Metal Nanocomposites with 2-Dimensional Au Nanoparticle Arrays for Sensoric Applications." *Journal of Physics: Conference Series*, 2008, vol. 100, part 5.
- Hanisch, C., A. Kulkarni, V. Zaporotjchenko and F. Faupel, Hyun Jin, Christopher R. Field, and Pehr E. Pehrsson. "Periodically Porous Top Electrodes on Vertical Nanowire Arrays for Highly Sensitive Gas Detection." *Nanotechnology*, 2011, no. 22, 355-501.
- Hatab, Nahla A., Gyula Eres, Paul B. Hatzinger, and Baohua Gu. "Detection and analysis of cyclotrimethylenetrinitramine (RDX) in environmental samples by surface-enhanced Raman spectroscopy." *Journal of Raman Spectroscopy* 41, no. 10 (2010): 1131-1136.

- Headquarters Air Force Medical Support Agency (AFMSA). "Bioenvironmental Engineering Electronic Field Manual." Vers. SP0700-00-D-3180/DO 0606. Alliance Solutions Group, Inc. November 2012. www.asg-inc.org (accessed 8 July 2015).
- Helene, Tiffany R. *Laboratory Sampling Guide*. No. AFRL-SA-WP-SR-2012-0008. School of Aerospace Medicine, Wright-Patterson AFB, OH, Occupational and Environmental Health Department, 2012.
- Hibbs, Andrew D., and Geoffrey A. Barrall. *Engineered Bio-Molecular Nano-Devices/Systems*. Electronic Biosciences Inc, San Diego, CA, 2009.
- Holthoff, Ellen, and Dimitra Stratis-Cullum. *A nanosensor for explosives detection based on molecularly imprinted polymers (MIPs) and Surfaced-enhanced Raman Scattering (SERS)*. No. ARL-TR-5092. Army Research Lab, Adelphi, MD, Sensors and Electron Devices Directorate, 2010.
- IDEXX. "Colilert®." Water Testing Solutions-Products and Services. <https://www.idexx.com/water/products/colilert.html> (accessed 11 October 2015).
- In, Hyun Jin, Christopher R. Field, and Pehr E. Pehrsson. "Periodically porous top electrodes on vertical nanowire arrays for highly sensitive gas detection." *Nanotechnology* 22, no. 35 (2011): 355-501.
- INFICON. "HAPSITE ER Chemical Identification System" Overview. <http://products.inficon.com/en-us/Product/Detail/HAPSITE-ER-Identification-System?path=Products%2Fpg-ChemicalDetection>. (accessed 11 October 2015).
- . "HAPSITE Smart Plus Chemical Identification System" Overview. <http://products.inficon.com/en-us/Product/Detail/HAPSITE-Smart-Plus-Chemical-Identification-System?path=Products%2Fpg-ChemicalDetection>. (accessed 11 October 2015).
- . "Headspace Sampling System." Products. <http://products.inficon.com/en-us/Product/Detail/Headspace-Sampling-System?path=Products%2Fpg-ChemicalDetection>. (accessed 11 October 2015).
- Kahn, Nicole, Ofer Lavie, Moran Paz, Yakir Segev, and Hossam Haick. "Dynamic Nanoparticle-Based Flexible Sensors: Diagnosis of Ovarian Carcinoma from Exhaled Breath." *Nano letters* (2015).
- Li, Jing, and Yijiang Lu. "Nanostructure-engineered chemical sensors for hazardous gas and vapor detection." In *Optics East*, pp. 222-231. International Society for Optics and Photonics, 2004.

- Li, Tianhua, Yonglong Li, Yujie Zhang, Chen Dong, Zheyu Shen, and Aiguo Wu. "A colorimetric nitrite detection system with excellent selectivity and high sensitivity based on Ag@ Au nanoparticles." *Analyst* 140, no. 4 (2015): 1076-1081.
- Li, Yingchun, Yuan Liu, Jie Liu, Jiang Liu, Hui Tang, Cong Cao, Dongsheng Zhao, and Yi Ding. "Molecularly imprinted polymer decorated nanoporous gold for highly selective and sensitive electrochemical sensors." *Scientific reports* 5 (2015).
- Lisowski, Carmen E., and James E. Hutchison. "Malonamide-functionalized gold nanoparticles for selective, colorimetric sensing of trivalent lanthanide ions." *Analytical chemistry* 81, no. 24 (2009): 10246-10253.
- Luo, Kun, Tao Huang, Yujia Luo, Haiming Wang, Chao Sang, and Xiaogang Li. "Thin Film Assembly of Gold Nanoparticles for Vapor Sensing via Droplet Interfacial Reaction." *Journal of Materials Science & Technology* 29, no. 5 (2013): 401-405.
- MSA – The Safety Company. "The Sirius® Multigas Detector" Data Sheet: Sirius Multigas Detector. <http://s7d9.scene7.com/is/content/minesafetyappliances/Sirius%20Bulletin%20-%20EN> (accessed 11 October 2015).
- Namour, P, M. Lepot, and N. Jarezic. "Recent Trends in Monitoring of European Water Framework Directive Priority Substances Using Micro-Sensors: 2007-2009 Review." *Sensors*, 2010, no. 10: 7947-7978. <https://hal.archives-ouvertes.fr/hal-00536853>. (accessed 22 September 2015).
- Nano.gov. "Benefits and Applications." National Nanotechnology Initiative. <http://www.nano.gov/you/nanotechnology-benefits>. (accessed 15 March 2015).
- Nanogloss.com. "Gold Nanoparticles 101." Wordpress.org. <http://nanogloss.com/nanoparticles/gold-nanoparticles-101/#axzz3lzuifzNG>. (accessed 17 September 2015).
- Nanosphere. "Verigene System." Nanosphere, Inc. <http://www.nanosphere.us/products/verigene-system>. (accessed 13 July 2015).
- "Sniffing Out Cancer with Improved 'Electronic Nose' Sensors." Nanowerk News, September 30, 2015. <http://www.nanowerk.com/nanotechnology-news/newsid=41468.php>.
- Narda Safety Test Solutions. "High Frequency Broad Band Meters." Products. http://www.narda-sts.us/products_highfreq_bband.php. (accessed 11 October 2015).
- National Institute of Occupational Safety and Health. "MF-34 NIOSH Manual of Analytical Methods." Centers for Disease Control and Prevention. March 15, 2013. <http://www.cdc.gov/niosh/docs/2003-154/> (accessed 1 March 2015).

“NRL SiN-VAPOR Technology,” Naval-Technology, August 19, 2013. <http://www.naval-technology.com/news/newsnrl-develops-sinvapor-technology>. (accessed October 7 2015).

Nilsson, Patrik, Axel Eriksson, Maria Messing, Christina Isaxon, Maria Hedmer, Håkan Tinnerberg, Bengt Meuller et al. "Laser Vaporizer-AMS for exposure assessment and detection of airborne engineered metal nanoparticles." In *European Aerosol Conference 2012*. 2012.

Occupational Safety and Health Administration. "OSHA 3360 - Reflections on OSHA's History." U.S. Department of Labor. January 2009. https://www.osha.gov/history/OSHA_HISTORY_3360s.pdf (accessed 10 March 2015).

———. "At-A-Glance: OSHA." U.S. Department of Labor. <https://www.osha.gov/Publications/3439at-a-glance.pdf> (accessed 10 March 2015).

———. "OSHA Occupational Chemical Database." U.S. Department of Labor. <https://www.osha.gov/chemicaldata/#target>. (accessed 10 March 2015).

———. "Ergonomics: The Study of Work – OSHA 3125 (Revised). United States Department of Labor, 2000. <https://www.osha.gov/Publications/osha3125.pdf> (accessed 23 September 2015).

———. "OSHA Safety and Health Topics: Confined Spaces" United States Department of Labor. <https://www.osha.gov/SLTC/confinedspaces/> (accessed 23 September 2015).

Ohlinger, Alexander, Andras Deak, Andrey A. Lutich, and Jochen Feldmann. "Optically trapped gold nanoparticle enables listening at the microscale." *Physical review letters* 108, no. 1 (2012): 18-101.

Pedersen, David B., and E. J. Duncan. *Surface Plasmon Resonance Spectroscopy of Gold Nanoparticle-Coated Substrates: Use as an Indicator of Exposure to Chemical Warfare Simulants*. No. DRDC-SUFFIELD-TR-2005-109. Defence Research and Development Suffield (Alberta), 2005.

Pedersen, D. S., and S. Wang. *Current flow through two dimensional arrays of metal nanoparticles as a novel sensor platform*. No. DRDC-SUFFIELD-TM-2009-068. Defence Research and Development Suffield (Alberta), 2009.

Physics Central. "The Golden Age of Gold". American Physical Society. <http://www.physicscentral.com/explore/action/gold.cfm> (accessed 17 September 2015).

Phys.org. "Better Bomb-Sniffing Technology with New Detector Material." *Phys.org*, November 4 2014. <http://phys.org/news/2014-11-bomb-sniffing-technology-detector-material.html>. (accessed 17 September 2015).

- . “New Device Warns Workers of High Levels of Airborne Metals in Minutes Rather Than Weeks.” *Phys.org*, May 31, 2012. <http://phys.org/news/2012-05-device-workers-highairborne-metals.html>. (accessed 17 September 2015).
- Prokes, S. M., O. J. Glembocki, and R. W. Rendell. *Highly Efficient Surface Enhanced Raman Scattering (SERS) Nanowire/Ag Composites*. Naval Research Lab, Washington, DC, Electronics Science and Technology Division, 2007.
- Pu, Mingo. “Scientists Found a Natural Nanostructure to Control the Flow of Light.” *Nanotechnology Now*, October 4, 2015. http://www.nanotech-now.com/news.cgi?story_id=52337. (accessed 10 September 2015).
- Quest® Technologies. “Basic Sound Level Meters” Raeco Rents Products Page. <http://www.raecorents.com/products/noise/3M-Quest-2200-SLM/3M-basic-sound-level-meter-bro.pdf>. (accessed 11 October 2015).
- RADēCO. “US Air Force and National Guard Air Sampling Kit”. Products. <http://www.radecoinc.com/products/usaf-kit>. (accessed 11 October 2015).
- Reusch, William. “Visible and Ultraviolet Spectroscopy.” Michigan State University Department of Chemistry. <http://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/Spectrpy/UV-vis/spectrum.htm>. (accessed 22 September 2015).
- Rowe, Aaron. “The 9 Best Nanotechnology-Powered Products.” *Discover Magazine*, June 29, 2010. <http://discovermagazine.com/galleries/zen-photo/n/nanotech-products>. (accessed 17 September 2015).
- ScienceDaily. “Chip-Based Technology Enables Reliable Direct Detection of Ebola Virus.” *ScienceDaily.com*, 25 September 2015. <http://www.sciencedaily.com/releases/2015/09/150925085341.htm>. (accessed 10 October 2015).
- SKC. “Air Sampling Pumps to 5 L/min”. Sampling Pumps. http://www.skcinc.com/catalog/index.php?cPath=100000000_101000000. (accessed 11 October 2015).
- Smardzewski, R. R., N. L. Jarvis, A. W. Snow, and H. Wohltjen. *Nanoelectronic chemical sensors: theory and experiment*. Geo-Centers Inc. Aberdeen Proving Ground, MD, 2004.
- Smiths Detection. “HazmatID Elite: Handheld FT-IR Chemical Identifier.” Products and Solutions: Chemical Identification. <http://www.smithsdetection.com/en/products-solutions/chemical-identification/57-chemical-identification/hazmatid-elite.html#.ViRDwfmrSuk>. (accessed 11 October 2015).
- Thermo Scientific. “FirstDefender™ RM Chemical Identification System.” Products. <http://www.thermoscientific.com/en/product/firstdefender-rm-chemical-identification-system.html>. (accessed 11 October 2015).

Tisch, Ulrike, and Hossam Haick. "Arrays of chemisensitive monolayer-capped metallic nanoparticles for diagnostic breath testing." *Reviews in Chemical Engineering* 26, no. 5-6 (2010): 171-179.

TSI. "IAQ-CALC Indoor Air Quality Meter 7545" Products. <http://www.tsi.com/iaq-calc-indoor-air-quality-meters-7545/> (accessed 11 October 2015).

United States Army Technical Manual (TM) 3-6665-319-10, *Water Testing Kit, Chemical Agents: M272 (NSN 6665-01-134-0885)*, 30 November 1983.

United States Environmental Protection Agency. "Drinking Water Contaminants." <http://water.epa.gov/drink/contaminants/index.cfm#List>. (accessed 2 September 2015).

———. "Laws and Executive Orders." <http://www2.epa.gov/laws-regulations/laws-and-executive-orders>. (accessed 10 March 2015).

———. "Our Mission and What We Do." <http://www2.epa.gov/laws-regulations/our-mission-and-what-we-do>. (accessed 10 March 2015).

———. "Summary of the Occupational Safety and Health Act – 29 USC §651 et seq. (1970)." <http://www2.epa.gov/laws-regulations/summary-occupational-safety-and-health-act>. (accessed 10 March 2015).

———. "Unregulated Contaminant Monitoring Program." <http://water.epa.gov/lawsregs/rulesregs/sdwa/ucmr/index.cfm>. (accessed 2 September 2015).

———. "When and How was the EPA Created?" <http://publicaccess.supportportal.com/link/portal/23002/23012/Article/23723/When-and-how-was-the-EPA-created> (accessed 10 March 2015).

United States National Nanotechnology Initiative. "Benefits and Applications." <http://www.nano.gov/you/nanotechnology-benefits> (accessed 1 February 2015).

United States Navy. "Information Paper: Hand Held Assay (HHA)." Navy Environmental and Preventive Medicine Unit TWO. [http://www.med.navy.mil/sites/nepmu2/Documents/lab/Hand%20Held%20Assays%20\(HHA\).pdf](http://www.med.navy.mil/sites/nepmu2/Documents/lab/Hand%20Held%20Assays%20(HHA).pdf). (accessed October 10, 2015).

VAPORSENS. *Home Page*. <http://www.vaporsens.com/> (accessed 7 October 2015).

VAPORSENS. *Product: VSENS Page*. <http://www.vaporsens.com/gas-vapor-sensors> (accessed 7 October 2015).

VAPORSENS. *Technology: Sensors Page*. <http://www.vaporsens.com/sensors/> (accessed October 7, 2015).

Wallace, Lance, and John Toon. "Using Technology to Detect Gamma Radiation." Georgia Tech Research Institute. <http://www.gtri.gatech.edu/casestudy/using-nanotechnology-detect-gamma-radiation> (accessed 7 October 2015).

Wang, Chao, and Chenxu Yu. "Detection of chemical pollutants in water using gold nanoparticles as sensors: a review." *Reviews in Analytical Chemistry* 32, no. 1 (2013): 1-14.

Wang, Na, Hai-Yan Zhao, Xue-Ping Ji, Xian-Rui Li, and Bei-Bei Wang. "Gold nanoparticles-enhanced bisphenol A electrochemical biosensor based on tyrosinase immobilized onto self-assembled monolayers-modified gold electrode." *Chinese Chemical Letters* 25, no. 5 (2014): 720-722.

Wang, Jinfen, Chao Bian, Jianhua Tong, Jizhou Sun, and Shanhong Xia. "Simultaneous detection of copper, lead and zinc on tin film/gold nanoparticles/gold microelectrode by square wave stripping voltammetry." *Electroanalysis* 24, no. 8 (2012): 1783-1790.

Webb, R.C., R.M. Pielak, P. Bastien, J. Ayers, J. Niitynen, and J. Kurniawan. "Thermal Transport Characteristics of Human Skin Measured in Vivo Using Ultrathin Conformal Arrays of Thermal Sensors and Actuators." *PLoS ONE*, 2015, no. 10, 118-131.

Xia, Fan, Xiaolei Zuo, Renqiang Yang, Yi Xiao, Di Kang, Alexis Vallée-Bélisle, Xiong Gong et al. "Colorimetric detection of DNA, small molecules, proteins, and ions using unmodified gold nanoparticles and conjugated polyelectrolytes." *Proceedings of the National Academy of Sciences* 107, no. 24 (2010): 10837-10841.

Zemanian, Thomas S., and Yuehe Lin. *Nano-Engineered Electrochemical Sensors for Monitoring of Toxic Metals in Groundwater: Development of Novel Square Wave Anodic Stripping Voltammetry Electrodes Using Self Assembled Monolayers on Mesoporous Supports*. PNNL-16445. Pacific Northwest National Lab Richland, WA, 2007.

Zhong, Chuan-Jian, Derrick M. Mott, Peter N. Njoki, Lingyan Y. Wang, Jin Luo, and George W. Miller. *Synthesis and Thin Film Assembly of Copper Nanoparticles for Sensing Contaminants in Aircraft Cabins*. State University of New York at Binghamton Research Foundation, 2008.